A STUDY OF THE OPTIMAL ALLOCATION OF
TOLERANCES AND CLEARANCES IN PLANAR LINKAGE MECHANISMS

by

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A thesis submitted to the University of Newcastle upon Tyne
for the Degree of Doctor of Philosophy

July, 1982
"Read - in the name of your Lord who has created - created man from a clot. Read - and your Lord is the most generous, who has taught the use of the pen - taught man that which he knew not."

Quran, XCVI, 1-5.
ACKNOWLEDGEMENTS

The author is indebted to Dr. M.R. Smith for his encouragement and guidance throughout this work. Also the author wishes to express his thanks to Professor L. Maunder for permitting the work to be carried out in the Department of Mechanical Engineering, and NUMAC Computing Centre for the use of their computing facilities. Thanks are also due to Mrs. Lynn Whiteford for her patience and accuracy in typing this thesis. Finally the author wishes to acknowledge the financial support of Kartoum Polytechnic, without which this work would not have taken place.

The work described in this thesis has not been submitted to any other University, and consists of original work by the author except where specific reference is made to the work of others.
The work falls into two separate parts, involving respectively kinematic and dynamic aspects of planar linkage mechanisms. The first and major part reported in Part I concerns the development of a procedure for optimal allocation of tolerances and clearances in plane linkage mechanisms. The theory developed takes into account the sensitivity of the mechanism output to small deviations in the parameter dimensions and the cost-tolerance relationships for the parameters. A procedure is then derived from the theory and incorporated into a computer program to allocate tolerances to linear dimensions and angles, and clearances to the joints in the mechanism. To demonstrate the applicability of the method to a wide range of planar linkage mechanisms, a number of examples are given which include 4-, 6-, 8- and 10-bar linkages.

Part II describes the investigation of possible methods for maintaining contact in the joints of a plane four-bar mechanism by means of mass redistribution, the aim being to reduce or eliminate vibration due to impact in joints with clearance. An optimization routine is used with constraints upon the magnitude of the joint forces and the rate at which those forces change direction based on a 'no-clearance' analysis. The method was applied to several examples with little success due to inherent limitations of the analysis method used.
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CHAPTER ONE

GENERAL INTRODUCTION
The work reported in this thesis is a study of plane linkage mechanisms regarding: (a) the allocation of tolerances and clearances, and (b) the redistribution of link masses to avoid contact loss in the joints. The study involves theoretical analysis and development of procedures which are subsequently incorporated into computer programs.

1.1 ALLOCATION OF TOLERANCES AND CLEARANCES

In the manufacture of parts it is impossible to produce parts having dimensions exactly equal to the nominal dimensions required by a certain design. Consequently a designer dimensions parts specifying tolerable upper and lower limits. For a part which is a component of an assembly, this tolerance on the part dimension depends on the allowable deviation on the overall or output dimension of the assembly.

Part I of this study deals with the allocation of tolerances on the link arc-lengths (i.e. distances between joint centres on a link) and arc-angles (i.e. angles between arcs on the same link), and clearances in the joints, for planar multi-link mechanisms with revolute joints. The tolerances and clearances are allocated such that the deviation in the output due to the tolerances and clearances does not exceed specified limits. Since the sensitivities of the output dimension to changes in arc lengths are not the same for the different dimensions, it follows that allocating the tolerances and clearances indiscriminately would not be wise because this would lead to the tolerances on the dimensions with low
sensitivity being tighter than necessary and on the dimensions with high sensitivity wider than required. Thus if all the tolerances are allocated to the tightness required for the more sensitive dimensions, the cost of manufacture would be unnecessarily high due to the extra tightness on the less sensitive dimensions. Similarly relaxing the tolerances indiscriminately would lead to the output dimension deviating beyond the specified limits. Hence for appropriate allocation of tolerances the sensitivities must be taken into account.

Assigning tolerances subject to sensitivities alone, though it leads to lower manufacturing cost, does not insure that the cost will be the minimum possible. This is because the cost-tolerance relationship is not a linear one. Hence for the distribution of the output tolerance among the component tolerances to be an optimum the total cost of the assembly must be reduced to the lowest possible by adjusting the tolerances appropriately.

This is achieved here by minimizing an objective function giving the total cost subject to the constraint that the output deviation due to the allocation of the tolerances, taking into account the sensitivities of the output to individual dimensions, does not exceed the specified limit. The solution is obtained using the Lagrange multiplier method. A procedure is then developed and incorporated into a computer program TOCALM for the allocation of optimum tolerances and clearances. A graph plotting program PSODPLOTS uses output from the above program to plot the sensitivities of the output
to individual dimensions and the output deviation band resulting from the allocation of the tolerances and clearances computed against crank input position for the mechanism. Results for a number of example linkages are reported.

1.2 MAINTAINING CONTACT IN JOINTS

The existence of clearances in the joints of mechanisms is inevitable. This leads to the possibility of loss of contact between pairing elements at the joint resulting in impact when contact is remade. Consequently this leads to noise, vibration, wear and possible failure. This problem is becoming more serious due to higher speeds at which modern machinery is required to run. Since clearances are inevitable the only alternative to evade this problem is to insure that contact between the pairing elements at the joints is maintained at all times.

To maintain contact at a joint certain conditions must be satisfied, viz. that the force between the elements of the joint must not approach zero or change direction too rapidly. There are two ways by which these conditions may be satisfied, (a) addition of masses, i.e. counterweights, such that joint forces are made favourable, or (b) attaching springs between the elements at the joints so that the joint forces are modified satisfactorily. Part II of this investigation is concerned with an attempt to satisfy the conditions of maintaining contact in the joints of a four-bar mechanism by optimizing the mass distribution, i.e. method (a) above. The mechanism is analyzed as an ideal mechanism with no clearances, and an
objective function is hence developed such that when it is minimized the conditions of maintaining contact are approached. The parameters of the additional masses constitute the optimization variables. The analysis is incorporated into a computer program named CONTACT and a further program named PINFORCE is written to produce polar plots of the joint forces. Results of applying the method to a number of example linkages are reported.
PART I

TOLERANCE AND CLEARANCE ALLOCATION
CHAPTER TWO

TOLERANCE AND CLEARANCE ALLOCATION:
LITERATURE SURVEY
2.1 INTRODUCTION

Though the treatment of the subject of tolerancing dates back many years, publications on the subject have been scanty. The publications which have appeared may be divided into several categories according to the emphasis on the various aspects of the subject. The works reported here include those categories concerned with the relationship between the overall (or output) tolerance of an assembly and the tolerances on the dimensions of the component parts.

2.2 ASSEMBLY TOLERANCING

There are two philosophies as regards the accumulation of tolerances in an assembly. The first is variously termed absolute tolerancing, sure-fit, complete interchangeability and additive. As the terms imply this method assumes that parts having dimensions on the extremes of the tolerance will be assembled with other parts also at the extreme of the tolerance, at least some, or possibly all, of the time. The second method is variously termed scientific, Pythagorean and statistical. This method is based on the fact that, as shown by Rice [1], parts produced in quantity have their dimensions distributed between the limits of the tolerance zone. As a result the functional dimension of the assembly (or the output deviation) will also be distributed between the limits of the output tolerance. According to the theory of probability, since the parts are randomly selected for assembly, it is extremely rare that parts with extreme dimensions are assembled together.
Acton and Olds [2], Motrecht and Caddell [6], and Brooks [11], assuming normal distributions for the parts dimensions show that the total tolerance of an assembly is more correctly represented by the square root of the sum of squares of the individual tolerances on the part dimensions. If what Acton and Olds term 'natural tolerances', i.e. ±3σ (three standard deviations), are allocated then only 0.27% of the assemblies will have dimensions outside the tolerance limits. Hence they deduce that statistical tolerancing is more economical because it allows wider part tolerances for a given output tolerance or accumulated assembly tolerance.

Spotts [9] uses the probabilistic law - that the variance of a combination of variables is equal to the sum of the variances of the individual variables - and normal distribution tables to determine the percentages of assemblies which will meet specified tolerances. He gives examples for assemblies of two components, but states that the method becomes more complicated for more than two components.

The additive method of tolerance accumulation may be economical or necessary if the number of parts produced is small or when high precision is involved. Moltrecht and Caddell [5] and Tuttle [10] use this method. Tuttle [10] also gives an output error equal to the root mean square of the part errors, but does not clarify its significance. Knappe [12] also uses the additive method taking into account the sensitivity of the output to individual part dimensions. He also notes that the output dimension of the assembly of randomly assembled
parts has a normal distribution even if the part dimensions have rectangular distributions. This fact was also shown by Acton and Olds [2] and Pike and Silverberg [3] to apply if the number of part dimensions involved is more than five.

A number of factors may cause the part dimension to depart from the normal distribution. Gladman [7] and Lorenz [8] report on these factors which result from the relationship between the part tolerance and the properties of the machining process such as the process tolerance and drift tendencies due to e.g. tool wear. Gladman [7] recommends adjusting the statistical tolerancing equation by a 'design factor' to safeguard against distributions that are not normal. Thoen [4] on the other hand recommends a computer simulation technique using punched cards representing frequency of occurrence of part dimensions to determine the distribution of the output dimension.

An important aspect of tolerancing assemblies is the change in dimensions due to storage, operation and wear. This is discussed by Sergeyev [25] who suggests proportioning the deviation in a part dimension into manufacturing error and age error. However this may be allowed for when specifying the assembly tolerance.

2.3 TOLERANCING FOR MINIMUM COST

Statistical tolerancing reduces cost by allowing the tolerances on the part dimensions to be wider. A further reduction is possible if the output or assembly tolerance is distributed among the individual components in a certain way.
Peters [18] reports on three methods, namely (1) distributing tolerances according to the size of each component, (2) according to the standard deviation, and (3) to achieve minimum assembly cost. A fourth method, that of distributing the tolerance equally, is implied by Sharfi and Smith [39].

Minimum cost is achieved by minimizing the total cost of an assembly subject to the constraint that output or assembly tolerance does not exceed a specified value. Pike and Silverberg [3] give a lengthy procedure to achieve minimum cost. A simple graphical method is described by Latta [13] whereby minimum cost is achieved by selecting the individual tolerances by trial and error such that the tangents to the cost-tolerance curves at the selected tolerances are parallel. This method requires cost-tolerance curves to be available and becomes tedious as the number of individual tolerances increases. An analytical equivalent of this method is given by Hillier [14] who uses a simple function to represent the cost-tolerance relationship and hence derives a simple expression for optimum tolerances. Peters [18] gives an involved procedure for assigning tolerances for assemblies with two component dimensions. He states that it becomes more involved for assemblies with more than two components and suggests that in such cases subassemblies should be considered applying the method successively. Simpler methods are reported by Speckhart [21] and Spotts [22], who use approximate cost-tolerance relationships. Speckhart [21] uses an exponential relationship, whereas Spotts [22] uses an inverse square
relationship. As reported by Peat [15], cost-tolerance relationships are very complex due to the factors comprising the cost such as time, overhead, inspection, scrap percentage, etc. However, useful approximate relationships may be obtained by curve fitting. For purposes of comparison, even a relationship derived from observing the cost of producing a given tolerance is adequate, Hillier [15]. Sutherland and Roth [27] also use an exponential cost-tolerance relationship to derive an objective function which is minimized subject to a constraint equation comprising output tolerance due to structural and mechanical errors.

2.4 TOLERANCING APPLIED TO LINKAGE MECHANISMS

The problem of tolerancing linkage mechanisms is a special case of assembly tolerancing. In addition to link length tolerances, clearances in the joints of the mechanism need to be considered. Garrett and Hall [16] are perhaps the pioneers in this area-especially with respect to the effects of clearance. They use a statistical approach using a digital computer to simulate random assembly of a sample of 300 mechanisms to obtain what they termed a 'mobility band' within which a given percentage of the mechanism tolerances will lie. This is used as a check for a direct method called the 'delta method' derived from probability theory to determine the mobility band quickly. However, the tolerances and clearances are specified first and do not result from the specification of the output tolerance. Kolhatkar and Yajnik [17] examined
the effect of joint clearances, treating them as 'equivalent links'. They considered four- and six-bar function generators, and found that in the four-bar the maximum output error due to clearance effects is obtained when all the clearance links are parallel to the coupler link. The method used is however deterministic. Skreiner and Ebeling [19] use a statistical approach employing Monte Carlo sampling to determine the output distribution for specified tolerances and clearances. In their analysis the clearance effects are included in the frame link length. Lakshminarayana and Narayanamurthi [20] give an analytical method and its graphical equivalent which are used to determine the effect of link length tolerances on the output in a deterministic or additive manner. The graphical method is derived from the velocity diagram and the analytical method is based on loop closure equations. The effects of clearance are not included. Coderman and Mabie [22] developed charts for predicting the maximum mechanical error for various combinations of tolerances, clearances and link length ratios of a four-bar linkage. The errors are equivalent to the maximum clockwise and anticlockwise displacement of the output for given input link position.

A departure from the above methods is that of Dhande and Chakraborty [24] who use a stochastic approach to allocate tolerances and clearances which satisfy a specified output tolerance. Tolerances and clearances are treated as optimization parameters and optimum values are allocated by dynamic programming using an iterative technique. In the analysis
tolerances are included with corresponding link lengths and the pin displacement within the clearance space is included in the link length of the preceding link rather than in the more sensitive of the links meeting at the joint. Chakraborty [26] uses a similar analysis to the above, but whereas the above starts at an arbitrary input position, allocates tolerances and clearances, then analyses the mechanism to find the position giving the worst deviation and repeats the process, this method includes the input position as a parameter in the dynamic programming. Sutherland and Roth [27] determine tolerances which result in a minimum cost. An objective function derived from a cost-tolerance relationship is minimised subject to a constraint equation comprising structural error and mechanical error arising from link length tolerances, and a maximum allowable error. Hence the mechanism is synthesized and tolerances on link lengths are allocated simultaneously. This is a significant development in synthesis, however the effects of clearance are not included in the analysis. Dubowsky et al. [28] through minimizing a criterion function equal to the difference between the actual mechanism response and a mathematical model response determine the unknown parameters which comprise link length errors and joint clearances. In the model, clearances are represented by vectors joining centres of mating connection parts, i.e. 'clearance links'. In the procedure used the clearances in all the joints appear to be acting as if combined into the coupler link and it is not possible to determine the clearance in each joint.
Rao [32] outlines an iterative method whereby a mechanism is synthesized taking into account the effects of link deformation, tolerances and joint clearances. However the tolerances and clearances are specified prior to the synthesis of the mechanism. Rao and Reddy [35], using the techniques of chance constrained programming, synthesize mechanisms for minimum structural and mechanical errors treating link lengths (nominal length ± tolerance) and joint clearances as random variables. In the analysis clearances are incorporated into the link length of the link preceding the respective joint, which as noted earlier may not be the more sensitive of the two links connected by the joint.

A variation of the above methods is that used by Horie et al. [36] who use what they term 'transformation functions' (which are open chains held at their extreme positions due to the forces acting in the joints) to determine the limit positions of the output of the mechanism at given input positions taking into account both clearances and tolerances. Choubey and Rao [38] use a method where the mechanical error is treated as a deviation in the structural error. Tolerances are then allocated with reference to the position of maximum error. However, since in the analysis nominal link lengths are determined prior to tolerance allocation, there is no difference between treating the mechanical error as a deviation in either the output or the structural error.
2.5 THE PRESENT WORK

The present work involves the development of a simple method and associated computer programs for the allocation of tolerances and clearances to multi-link plane mechanisms with revolute joints in such a way that the cost due to tolerances is a minimum. It is felt that this will provide a needed tool in the computer aided design of mechanisms. To the best knowledge of the author such a tool is lacking. The program is designed to fit in a package for the design of linkage mechanisms at the Design Unit of the Department of Mechanical Engineering, University of Newcastle upon Tyne.
CHAPTER THREE

TOLERANCE AND CLEARANCE ALLOCATION: THEORY AND ANALYSIS
3.1 INTRODUCTION

The analysis presented here applies to plane one degree of freedom mechanisms with turning pairs. It does not cater for mechanisms with sliding joints because of the complexity of the error arising from play in sliding joints in the cases where the slide is longer than the guide (as depicted by Fig. 3.1). However the cases where the sliding pair is of the type shown in Fig. 3.2(a) the error due to play is comparable to that of a turning pair (Fig. 3.2(b)).

The output of a mechanism may be measured by a single coordinate - function generator mechanism, or by two coordinates in the case of path generators. The analysis is developed for the first case and then extended to include the second.

3.2 CASE WHERE OUTPUT IS DEFINED BY ONE COORDINATE

3.2.1 Relationship between Output Deviation and Parameter Deviations

Consider the mechanism shown schematically in Fig. 3.3. Output is measured by the coordinate which is a function of the dimensional parameters of the mechanism, and the input to the mechanism, i.e. crank position . The parameters of the mechanism consist of the arc lengths 'a' and arc angles 'γ'. In this context an 'arc' is defined as the centre distance of two joints on a link. For a link with more than two joints (ternary, etc.) the angle between two arcs intersecting at a
joint is termed an 'arc angle'. Hence for a ternary link the
relative positions of the joints are defined by two arcs and
the arc angle between the two arcs.

The output $\phi_j$ corresponding to input position $\theta_j$ may be
represented as:

$$\phi_j = f(a_{1,1}, a_{2,1}, \ldots, a_{r,1}, \ldots, a_{1,l}, a_{2,l}, \ldots, a_{r,l}, \gamma_{1,1}, \gamma_{2,1}, \ldots, \gamma_{r,1}, \ldots, \gamma_{1,l}, \gamma_{2,l}, \ldots, \gamma_{r,l}, \gamma_c, \gamma_o, \theta_j)$$

The suffixes for the arcs and arc angles refer to the number
of arc in the loop and the number of the loop. According to the
 topology used here, Oldham, for linkages formed by the
addition of one or more dyads (a dyad being a pair of links with
 a common joint) to a basic unit consisting of a frame and a
single input link pivoted to it, the addition of each dyad results
in the formation of a new independent loop. The input link
pivot is taken as the starting point for each loop for numbering
the arcs traversed in the loop. In the first loop the first
arc is always the input arc, i.e. $a_{1,1}$. In the other loops, the
first arc may be associated either with the input link or the
frame. In all loops, the last arc is associated with the frame
with the loop closing at the input link pivot. The remaining
arcs are numbered consecutively around the loop. Two or more
arcs traversed in different loops are regarded as common if they
remain at a fixed angle relative to each other during the
motion of the mechanism, i.e. they lie on the same link. These
fixed angles are termed arc angles. An arc angle is identified by the same suffixes as the arc traversed in the latter loop.

\( \gamma_c \) and \( \gamma_0 \) are the input and output reference angles respectively. 'r' is the number of arcs in the largest loop, i.e. with greatest number of arcs, and 'l' is the number of independent loops in the mechanism.

To make the above expression concise, substitute a general parameter array 'v' for the a's and \( \gamma \)'s, hence expression 3.1 may be rewritten as

\[
\phi_j = f(v_1, v_2, \ldots, v_n, \theta_j) \quad \text{3.2}
\]

\[
\text{where } n \leq 2rl + 2
\]

The deviation of the parameters \( v_i \) from their nominal values due to arc length and arc angle tolerances and joint clearances will cause the output to deviate from the desired value corresponding to the nominal dimensions of the parameters. This deviation of the output is known as the 'mechanical error' and is inevitable as are the tolerances and clearances. Hence it is necessary to specify a tolerable output deviation, and, based upon it, the tolerable parameter deviations may be determined.

3.2.2 Statistical Considerations

The tolerable parameter deviations are, of course, the maximum acceptable deviations when the parts are manufactured. However the actual part dimensions will be distributed within the specified tolerance zones. In an assembly, parts are selected
randomly and fitted together. The error in the output dimension of the assemblies will hence be distributed within certain limits. The distribution of the output error may be derived from the distributions of the dimensions of the individual parts. The distributions of the part dimensions is determined by the behaviour of the machining process used in the manufacture rather than by the number of parts produced at any one time. Hence statistical considerations are valid even if a small number of parts is produced at a time.

The statistical parameters of the output dimension of an assembly are calculated based on the statistical parameters of the part dimensions and on how these dimensions influence the output dimension, i.e. the sensitivities of the output dimension to changes in the part dimensions. From statistical theory, Haugen [37], the relationship between the standard deviation of the output dimension, \( \sigma_T \), and those of the individual part dimensions, \( \sigma_i \), may be expressed as:

\[
\sigma_T^2 = \sum_{i=1}^{n} P_i^2 \sigma_i^2
\]

where \( P_i \) is the sensitivity of the output dimension to a change in the \( i \)th part dimension.

If the tolerable deviation, \( \delta_i \), on a dimension is written as a multiple of the standard deviation, i.e.

\[
\delta_i = k_i \sigma_i
\]
where \( k_i \) is a constant, then equation 3.3 may be rewritten in the form

\[
\frac{\Delta^2}{k_T^2} = \sum_{i=1}^{n} P_i^2 \frac{\delta_i^2}{k_i^2}
\]  

3.5

where \( \Delta = k_T \sigma_T \)

Since for most manufacturing processes the distribution is 'normal', an equal confidence level (i.e. proportion of accepted parts of the total parts produced) for each of the parts and the assembly may be assumed. This means that the \( k \)'s in the above equation will be equal and may be eliminated. The commonly used value is '3', corresponding to 'three standard deviations' or so called 'natural tolerance', which means that 99.73 per cent of the parts produced will be accepted. Thus equation 3.5 becomes

\[
\Delta^2 = \sum_{i=1}^{n} P_i^2 \delta_i^2
\]  

3.6

For a mechanism the influence coefficients, \( P_i \), may vary with input position. Then for any position \( \theta_j \) of the input equation 3.6 will take the form

\[
\Delta_j^2 = \sum_{i=1}^{n} (P_i)_j^2 \delta_i^2
\]  

3.7

The influence coefficient, \( (P_i)_j \), is the sensitivity of the output dimension to changes in the part dimensions and is
defined by the partial derivative $\frac{\partial \phi_j}{\partial \nu_j}$.

If the specified allowable output deviation is $\Delta_*$ and the maximum influence coefficient for parameter 'i' over the cycle of motion of the mechanism is $P_i*$, then the condition that

$$\Delta_*^2 = \sum_{i=1}^{n} P_{i*}^2 \delta_i^2$$

will satisfy the requirement $\Delta_j \leq \Delta_*$, i.e. the output deviation at every position will be within the tolerance limit. Since the $P_{i*}$ do not necessarily coincide at the same position in the cycle of motion of the mechanism, the $\delta_i$'s determined by equation 3.8 are multiplied by a scaling factor (see section 3.4).

3.2.3 **Simple Tolerance Allocation**

A simple method which readily lends itself to determine the $\delta_i$'s satisfying equation 3.8 is to assume that the output deviation is equally shared among the part dimensions contributing to the output dimension, i.e.

$$P_{i*} \delta_i = \tau = \text{constant}$$

Hence, substituting into equation 3.8

$$\Delta_*^2 = n \tau^2$$
Then the tolerance for each individual part dimension is given by

\[ \delta_i = \frac{\Delta_*}{\sqrt{n} \cdot P_{i*}} \]  

3.10

Results obtained by applying this simple method are reported in Sharfi & Smith [39] and compare favourably with results obtained by other investigators using much more complex methods (see section 6.2). The method however does not take into consideration the effect of cost. As is readily obvious from equation 3.10 the dimensional tolerance \( \delta_i \) is inversely proportional to the influence coefficient \( P_{i*} \) since \( \Delta_* \) and \( n \) are constant. It follows that for dimensions with high influence coefficients, the tolerances allocated will be very small and therefore very expensive to achieve.

In the following sections a method which takes cost effects into account is derived and thereby tolerances are allocated such that the total cost for producing the parts is a minimum.

3.2.4 **Cost Considerations**

The cost of manufacturing a machine part depends, among other factors such as material, manufacturing process, etc., on the tolerances on the dimensions of the part. In effect tolerances represent a critical component of the total cost, the more tight the tolerances are the higher will be the cost of the part. Empirical cost-tolerance relationships may be derived from cost tolerance charts for different machining
processes. Hillier [14] and Spotts [23] represent the cost $C_i$ of producing a component by the relationship

$$C_i = A_i + \frac{B_i}{\delta_i^2}$$  \hspace{1cm} 3.11

where $A_i$ is a constant comprising the cost of the component excluding the tolerance cost, and $B_i$ is a constant representing the cost of producing the dimension involved to some given tolerance. While Speckhart [21] recommends the relationship

$$C_i = M_i + L_i e^{K_i\delta_i}$$  \hspace{1cm} 3.12

where $M_i$, $L_i$ and $K_i$ are constants determined by curve fitting to cost tolerance data.

Both these relationships represent reasonable approximations to the cost tolerance relationship which is a rather complex relationship owing to the many factors involved, Peat [15]. However, since the objective is one of comparing the relative costs for the parts of an assembly, either of these relationships is adequate for the purpose of the present study. The first relationship, which is simpler to manipulate will be used in the analysis which follows.

3.2.5 Optimized Tolerance Allocation

An optimized tolerance allocation of the dimensions of parts of an assembly is one which, besides satisfying the requirement that the output deviation lies within specified
limits, will ensure that the total cost of the assembly will be a minimum.

Using relationship 3.11 above, the total cost \( C \) of an assembly is given by:

\[
C = \sum_{i=1}^{n} \left( A_i + \frac{B_i}{\delta_i^2} \right)
\]  

3.13

Hence for an optimum tolerance allocation \( C \) must be made a minimum subject to the constraint given by expression 3.8. Using the Lagrange multiplier method, this condition is satisfied if

\[
\frac{\partial C}{\partial \delta_i} + \lambda \frac{\partial \delta_i}{\partial \delta_i} = 0 
\]  

3.14

where \( \lambda \) is the Lagrange multiplier.

Differentiating expression 3.8 and 3.13, and substituting in 3.14 gives

\[
-\frac{2B_i}{\delta_i^3} + \lambda \frac{P_{i*}^2 \delta_i}{\Delta_*} = 0
\]  

3.15

The multiplier \( \lambda \) is of no interest and may be eliminated as follows: rewriting equation 3.15 for any other parameter \( r \), i.e.

\[
-\frac{2B_r}{\delta_r^3} + \lambda \frac{P_{r*}^2 \delta_r}{\Delta_*} = 0
\]  

3.16

and substituting for \( \lambda \) in 3.15 from 3.16 gives after rearranging
\[
\frac{\delta_i}{\delta r} = \left( \frac{P_{r*}^2 B_i}{P_{i*}^2 B_r} \right)^{\frac{1}{2}}
\]

Substituting for \( \delta_i \) in equation 3.8 gives

\[
\Delta_*^2 = \sum_{i=1}^{n} P_{i*}^2 \left( \frac{P_{r*}^2 B_i}{P_{i*}^2 B_r} \right)^{\frac{1}{2}} \delta_r^2
\]

\[
= \frac{P_{r*} \delta_r^2}{\sqrt{B_r}} \sum_{i=1}^{n} P_{i*} \sqrt{B_i}
\]

\[
\therefore \delta_r = \frac{\Delta_* B_r^{\frac{1}{4}}}{\sqrt{P_{r*} \sum_{i=1}^{n} P_{i*} \sqrt{B_i}}}
\]

Hence the maximum tolerable deviations \( \delta_r \) \((r = 1, 2, \ldots, n)\) on the part dimensions giving an optimum total cost may be computed for a given output tolerance \( \Delta_* \) and tolerance cost constants \( B_r \). The influence coefficients \( P_r \) are determined by partial differentiation of expression 3.2.

For complex multi-link mechanism, relationship 3.2 is difficult to compute analytically, and it is therefore more convenient to perform the differentiation numerically. Hence

\[
(P_i)_j = \frac{\partial \phi_j}{\partial v_i}
\]

is given by

\[
(P_i)_j = \frac{f(v_1, v_2, \ldots, v_i + \epsilon_i, \ldots, v_n, \theta_j) - f(v_1, v_2, \ldots, v_i - \epsilon_i, \ldots, v_n, \theta_j)}{2 \epsilon_i}
\]

3.19
where $\epsilon_i$ is the numerical differentiation step. To improve the accuracy and reliability of the numerical differentiation the computation using expression 3.19 is repeated once. In the first instance step values $\epsilon_i$ of the order of manufacturing tolerances are used. In the second instance step values equal to the allowable deviations ($\epsilon_i = \delta_i$) obtained using the partial derivatives computed in the first instance are used. In fact the computation should be repeated continuously until the step values used and the resulting allowable deviations are equal. However this was found not to be necessary because it was observed that after the second computation the difference between successive evaluations was within $\pm 2\%$.

To safeguard against cases where the gradient $\partial f / \partial v_i$ changes sign across the mean value of parameter $v_i$ as depicted by Fig. 3.4, and since it is the absolute value of the partial derivative, as the parameter value deviates to either side of the mean, which matters in the present context, equation 3.19 may be rewritten in the form

$$
(P_i)_j = \frac{1}{2\epsilon_i} \left( f(v_1, v_2, \ldots, v_i + \epsilon_i, \ldots, v_n, \theta_j) - f(v_1, v_2, \ldots, v_i, \ldots, v_n, \theta_j) \right) + f(v_1, v_2, \ldots, v_i, \ldots, v_n, \theta_j) - f(v_1, v_2, \ldots, v_i - \epsilon_i, \ldots, v_n, \theta_j) \right)
$$

This in effect gives the average value of the gradients for the positive, $(P_i)_j^+$, or forward deviation from mean, and the negative, $(P_i)_j^-$, or backward deviation. In the present work
tolerances are treated as symmetrical about the mean value of a dimension. For asymmetrical tolerancing, if future developments require, equation 3.20 may be separated into two components giving \((P_i)_j^+\) and \((P_i)_j^-\), and the corresponding asymmetrical tolerances \(\delta_i^+\) and \(\delta_i^-\) computed.
3.3 CASE WHERE OUTPUT IS DEFINED BY TWO COORDINATES

In the path generator mechanism shown in Fig. 3.5, the output is the position of the coupler point \( P \). To define the position of \( P \), two coordinates are needed whether cartesian or polar coordinates are used. Hence using cartesian coordinates and an \( x-y \) reference frame the output position corresponding to input position \( \theta_j \) may be defined as

\[
x_j = f_x(v_1, v_2, \ldots, v_n \theta_j)
\]

\[
y_j = f_y(v_1, v_2, \ldots, v_n \theta_j)
\]

The output deviations in the \( x \)- and \( y \)-directions are given by

\[
\Delta x_j^2 = \sum_{i=1}^{n} (P_{xi})_j^2 \delta_i^2
\]

\[
\Delta y_j^2 = \sum_{i=1}^{n} (P_{yi})_j^2 \delta_i^2
\]

If the allowable deviations in the \( x \)- and \( y \)-directions are \( \Delta x^* \) and \( \Delta y^* \) the corresponding expressions to 3.8 in the preceding case are

\[
\Delta x^*_j = \sum_{i=1}^{n} P_{xi*}^2 \delta_i^2
\]

\[
\Delta y^*_j = \sum_{i=1}^{n} P_{yi*}^2 \delta_i^2
\]
Hence, for minimum total cost, the Lagrange multiplier method gives the condition that

\[
\frac{\partial C}{\partial \delta_i} + \lambda \frac{\partial \Delta_x}{\partial \delta_i} + y \frac{\partial \Delta_y}{\partial \delta_i} = 0 \tag{3.24}
\]

Substituting corresponding expressions for the derivatives gives

\[
-2B_i \frac{\partial i}{\partial \delta_i} + \lambda \frac{p_{x_i}^2 \delta_i}{\Delta_x} + y \frac{p_{y_i}^2 \delta_i}{\Delta_y} = 0 \tag{3.25}
\]

This equation may only be solved by an iterative technique. The solution was attempted using NAG Library routine E04WAE (71), which incorporates an algorithm for finding a minimum of a function (which here, corresponds to the total cost given by equation 3.13) of several variables (here, the allowable deviations on the dimensions) subject to equality constraints (here, equations 3.23). The routine uses a sequential augmented Lagrangian method. However convergence to a satisfactory solution was not achieved, and moreover, being an iterative process, the solution was found to take more than fifty times that of the analytical solution for the one coordinate system case (section 3.2). The attempt was therefore abandoned in favour of an approximate method devised to convert the problem to one similar to that of the 'one coordinate' case presented in the preceding section 3.2.
Consider the expression

$$\Delta_{x^*}^2 = \sum_{i=1}^{n} \max (p_{x_i^*}, p_{y_i^*}) \delta_i^2$$

where $\rho = \Delta_{x^*}/\Delta_{y^*}$. This expression satisfies both equations 3.23. Thus the two constraint equations have been reduced to a single one, and hence forth, the solution is similar to that given in the foregoing section 3.2.5.
3.4 SCALING FACTOR

In the preceding analysis the term $P_i^*$ corresponding to the maximum of $(P_i)_j$ was used. However the $P_i^*$'s may not necessarily coincide at one input position. Hence the allowable parameter deviations, $\delta_i$, computed using equations 3.10 or 3.18 will be smaller than necessary. Substituting these computed deviations into equation 3.7 will give the variation of the actual output deviation, $\Delta_j$, over the cycle of motion of the mechanism. Due to the reason mentioned above, the maximum of $\Delta_j$ may be smaller than the allowable output deviation $\Delta_*$. Hence the parameter deviations $\delta_i$ have to be multiplied by a scaling factor $c_f$ defined by

$$c_{f1} = \frac{\Delta_*}{\max(\Delta_j)}$$

3.27

for the case where the output is defined by one coordinate, and

$$c_{f2} = \text{Smaller} \left( \frac{\Delta_{x*}}{\max(\Delta_{xj})}, \frac{\Delta_{y*}}{\max(\Delta_{yj})} \right)$$

3.28

for the case where the output is defined by two coordinates.
CHAPTER FOUR

TOLERANCE AND CLEARANCE ALLOCATION:
PROCEDURE FOR ALLOCATION
4.1 INTRODUCTION

The allowable deviation $\delta_i$ on a parameter dimension determined by the analysis of Chapter III is the total deviation on the parameter dimension which, for an arc length parameter, comprises the tolerance on the arc length and the associated clearances in the joints at the ends of the arc, as seen from Fig. 4.1; and for an arc angle parameter, comprises the tolerance in the arc angle and the associated clearances in the joints at the far ends of the arcs defining the arc angle as depicted in Fig. 4.2.

In this chapter a procedure is described whereby the allowable deviations $\delta_i$ are distributed between the tolerances and associated clearances. The clearance size in a joint has a distribution about a mean which is determined by the distributions of the dimensions of the pin and bore that constitute the joint pair. These dimensions have a 'normal' or Gaussian distribution, (Gladman [7]) and hence the clearance will also have a normal distribution. Hence in distributing the allowable deviation between the tolerances and clearances, the sum of squares law, i.e. the square of the allowable deviation being equal to the sum of squares of the tolerance and the associated clearances, will be applied.

4.2 ARC-LENGTH PARAMETERS

With reference to Fig. 4.1, the effective arc-length $a_{m,r}$ (i.e. arc number 'm' in loop number 'r') may be expressed as

$$a_{m,r} = \bar{a}_{m,r} \pm \delta_i$$
where $a_{m,r}^0$ is the nominal dimension of the arc-length, and $\delta_i$ is the corresponding allowable deviation on this parameter (i.e. arc length $a_{m,r}$ corresponds to the general parameter $v_i$ - see Chapter II, section 3.2.1). Then applying the sum of squares law gives the relationship

$$\delta_i^2 = t_{m,r}^2 + c_{m,r}^2 + c_{m,n,r}^2$$  \hspace{1cm} (4.2)

where $t_{m,r}$ is the tolerance on the arc length and $c_{m,r}$ and $c_{m,n,r}$ are the clearances in the joints connecting arc $a_{m,r}$ to arcs $a_{r}$ and $a_{n,r}$ respectively.

4.3 ARC-ANGLE PARAMETERS

For the ternary link shown in Fig. 4.2, the effective arc-angle $\gamma_{p,s}$ may be expressed as

$$\gamma_{p,s} = \gamma_{p,s}^0 \pm \delta_j$$  \hspace{1cm} (4.3)

where $\gamma_{p,s}^0$ is the nominal size of the arc-angle and $\delta_j$ is the corresponding allowable deviation on this parameter ($\gamma_{p,s} \equiv v_j$). Then, according to the sum of squares law the relationship between the allowable deviation and the tolerance and associated clearances may be expressed as

$$\delta_j^2 = e_{p,s}^2 + \left(\frac{c_{p,q,s}}{a_{p,s}}\right)^2 + \left(\frac{c_{k,r}}{a_{k,r}}\right)^2$$  \hspace{1cm} (4.4)

where $e_{p,s}$ is the tolerance on the arc angle and $c_{p,q,s}$ and
clearances in the joints at the far ends of the arcs $a_p,s$ and $a_k,r$ which define the arc angle (the error in the arc angle due to a clearance being the ratio of the clearance to the respective arc).

4.4 Procedure for Evaluation of Tolerances and Clearances

Relationships 4.2 and 4.4 above form the basis for the evaluation of the tolerances on the arc-lengths and arc-angles and the clearances in the joints of the mechanism. However to be able to use these relationships a ratio of the clearance component of the total deviation to tolerance component must be assumed, i.e. assume a ratio $\rho_a = \frac{c_{k,m,r}}{t_{m,r}} = \frac{c_{m,n,r}}{t_{m,r}}$ in the case of arc-length parameters, and $\rho_g = \frac{c_{p,q,s}}{a_p,s} \frac{c_{p,s}}{a_{p,s}}$ in the case of arc-angle parameters. The designer may choose suitable values for $\rho_a$ and $\rho_g$ based on experience and on the machining processes used in the manufacture of the parts. Garrett and Hall [16] used a value of $\rho_a = 0.5$, for example. Their choice was perhaps based on the relative ease of achieving tolerances and clearances in a machining process: clearances are affected by tool error only, whereas tolerances are affected in addition to tool error by positioning error.

Having chosen suitable values for the clearance to tolerance ratios, tolerances and clearances are evaluated according to the following steps:
(i) Arrange the allowable arc-length deviations $\delta_i$ in an ascending order.

The effect on the output deviation of a given clearance is greatest when the clearance is aligned with the most sensitive of the dimensions with which the clearance is associated. Therefore to minimize this effect a clearance must be allocated based on the allowable deviation of the most sensitive of the dimensions with which it is associated. Any clearance is associated with at least two arc length dimensions. Some may be associated in addition with arc angle dimensions, since there are in general fewer arc angles than arc lengths. The procedure for evaluating tolerances and clearances is hence structured with the above reasoning in mind.

Since not all clearances are associated with arc angles only the arc length deviations need to be arranged in a sequence according to value. Situations where a clearance is also associated with an arc length are accommodated when they are encountered, while following the arc length sequence, by checking whether the arc angle dimension is more sensitive (step (iii)) and the tolerances and clearances are allocated accordingly.
(ii) For parameter with the smallest deviation determine the arc length tolerance and associated joint clearances using relationship 4.2 and ratio $\rho_a$, i.e.

$$t_{m,r} = \frac{\delta_i}{\sqrt{1 + 2\rho_a^2}}$$

and

$$c_{m,m,r} = c_{m,n,r} = \rho_a t_{m,r}$$

(iii) If a clearance just computed is also associated with an arc-angle, the arc-angle and associated clearances are determined using relationship 4.4 and ratio $\rho_g$:

$$\epsilon_{p,s} = \frac{\delta_j}{\sqrt{1 + 2\rho_g^2}}$$

and

$$c_{p,q,s/a_{p,s}} = c_{k,l,r/a_{k,r}} = \rho_g \epsilon_{p,s}$$

The smaller value for the clearance in question (i.e. the value obtained using the arc-angle deviation and that obtained using the arc-length deviation) is then taken. The computation which gave the higher value is then repeated excluding the said clearance from the relationship. Thus if in the above the value for $c_{k,l,r}$ obtained by 4.6 was smaller than that obtained using
equations corresponding to 4.5, then the equation for the arc-length deviation would be modified to

\[ t_{m,r} = \frac{\delta_i}{\sqrt{1 + \rho_a^2}} \]

i.e. a clearance associated with an arc-angle deviation as well as an arc-length deviation is included with the deviation giving the smaller value for the clearance and excluded from the other.

(iv) The next arc-length deviation is then considered. If any of the associated clearances has been determined in a preceding computation, it is excluded as above. Hence if one of the clearances has been determined equation 4.5 is adjusted to

\[ t_{m,r} = \frac{\delta_i}{\sqrt{1 + \rho_a^2}} \]

and if both clearances have been determined

\[ t_{m,r} = \delta_i \]

(v) Go to step (iii) and continue.

Note: In the above procedure the determination of the clearance in a joint is such that it is included in the deviation which gives the smaller value and excluded from the deviations of the other parameters with which the joint is associated. This
is done so that (a) double counting is avoided, i.e., including the effect of clearance with more than one deviation, and (b) the possibility that, at worst, the 'clearance link', i.e. the vector between the pin and bore centres, may be aligned with the parameter whose deviation gives the smaller value for the clearance is accommodated.

4.5 TRANSFORMATION OF ARC-ANGLE TOLERANCE

In some situations a designer may find it inconvenient to specify angle tolerances. In such situations the angle tolerances may be transformed into length tolerances along cartesian coordinates. With reference to Fig. 4.3 the tolerances in arc-angle \( \gamma_{m,n} \) and arc-length \( a_{m,n} \), i.e. \( \varepsilon_{m,n} \) and \( t_{m,n} \), may be transformed into tolerances in the lengths \( u \) and \( v \) as follows:

\[
\begin{align*}
  u &= a_{m,n} \cos \gamma_{m,n} \\
  v &= a_{m,n} \sin \gamma_{m,n}
\end{align*}
\]

Denoting the tolerance in \( u \) by \( t_u \) and in \( v \) by \( t_v \), then

\[
\begin{align*}
  t_u &= \left| \frac{\partial u}{\partial a_{m,n}} \right| t_{m,n} + \left| \frac{\partial u}{\partial \gamma_{m,n}} \right| \varepsilon_{m,n} \\
  &= |\cos \gamma_{m,n}| t_{m,n} + |-a_{m,n} \sin \gamma_{m,n}| \varepsilon_{m,n} \\
  &= \frac{u}{a_{m,n}} t_{m,n} + v \varepsilon_{m,n}
\end{align*}
\]
\[
\begin{align*}
t_v &= \left| \frac{\partial v}{\partial a_{m,n}} \right| t_{m,n} + \left| \frac{\partial v}{\partial \gamma_{m,n}} \right| \varepsilon_{m,n} \\
&= \left| \sin \gamma_{m,n} \right| t_{m,n} + \left| a_{m,n} \cos \gamma_{m,n} \right| \varepsilon_{m,n} \\
&= \frac{v}{a_{m,n}} t_{m,n} + u \varepsilon_{m,n}
\end{align*}
\]

As this transformation is an option the designer may or may not opt for, it has not been incorporated in the computer program.
CHAPTER FIVE

TOLERANCE AND CLEARANCE ALLOCATION:
COMPUTER PROGRAMS
5.1 INTRODUCTION

Two programs are described in this chapter. Both are written in FORTRAN IV language. The first program, named TOCALM (Tolerance and Clearance Allocation in Linkage Mechanisms), incorporates the theory and analytical procedure developed in Chapters III and IV to determine tolerances and clearances for plane linkage mechanisms with revolute joints. The second, named PSODPLOTS (Parameter Sensitivities and Output Deviation PLOTS), uses the parameter sensitivities and the output deviation due to tolerance and clearance allocation calculated by the above program to produce graph plots of parameter sensitivities and output deviation against the input to the mechanism.

5.2 PROGRAM TOCALM

This program consists of a MAIN routine and twelve subroutines. Fig. 5.1 shows the flow chart for the program and a listing of the program is given in Appendix IA. Three of the subroutines, namely KALM, SETUP and SOLVE are an adaptation of Oldham's [31] program KALM (Kinematic Analysis of Linkage Mechanisms). The following sections give a description of the routines of the program and its operation.

5.2.1 Routine MAIN

This is the controlling unit of the program. The functions it performs are as follows:
(i) It reads the input data which consists of the topological description of the mechanism, dimensions of mechanism parameters, mechanism input positions, tolerance-cost constants and the mechanism output tolerance. A description of the input data and a sample input are given in Appendix IB.

(ii) It stores the topological data in pseudo arrays for use in subroutine RESET.

(iii) It examines the topological data to identify identical and non-identical common arcs. A common arc is one which is on the same link as another on a different loop. If the arc angle between the common arcs is zero and they have the same length then they are termed identical, otherwise, i.e. if the lengths are different or the angle is non-zero, they are termed non-identical.

(iv) It computes the partial derivatives and identifies their maximum values over the cycle of motion of the mechanism.

(v) It computes the allowable parameter deviations.

(vi) It controls the flow of the program and calls the subroutines at specific stages to perform the operations described in the following sections.

5.2.2 Subroutine KALM

This routine is called from MAIN to compute the output positions corresponding to an array of crank input positions
and a given set of mechanism parameter dimensions. MAIN calls KALM, first with the dimensions set at their nominal, or mean, values, and subsequently each time a parameter dimension is altered by adding or subtracting the corresponding numerical differentiation step. The values returned to MAIN are then used to perform the numerical differentiations.

KALM was chosen because it uses a topology capable of handling multi-link mechanisms, and also to enable the Design Unit at the Department of Mechanical Engineering in the University of Newcastle upon Tyne to build up a comprehensive package for linkage mechanism design whose components use the same input data structure.

5.2.3 Subroutine SETUP

This routine is called from KALM to convert the topological description of a linkage into an appropriate form for the next routine SOLVE.

5.2.4 Subroutine SOLVE

SOLVE is called from KALM to solve the kinematics for the linkage and hence compute the output position. In Oldham's [31] program this routine computes displacements, velocities and accelerations. Since only the output position is required for the present investigation, only the statements for computing displacements have been retained.

5.2.5 Subroutine RESET

Within the routine SETUP above, the arrays describing
the topology are altered to suit routine SOLVE. Since MAIN calls KALM repeatedly it is necessary to reset the topological description to its initial form. RESET is called from MAIN, prior to subsequent calls to KALM, to reset the topological arrays using the pseudo arrays set up by MAIN.

5.2.6 **Subroutine COMARC**

For linkages with more than one loop it is possible that there be identical common arcs as defined above. The common arcs will have different sensitivities in the different loops in which they are traversed. Hence it follows that the same arc will have allocated to it different allowable deviations corresponding to the sensitivity values determined for it as an arc in the respective loops.

This routine is therefore called from MAIN to allocate the same allowable deviation to the common arcs. The allowable deviation allocated is of course the smallest of the allowable deviation for the arc in the different loops.

5.2.7 **Subroutine CORFAC**

In section 3.5 Chapter III it was shown that the allowable deviations computed need to be multiplied by a scaling factor before they are used to determine tolerances and clearances. This routine is called from MAIN to compute the scaling factor, i.e. the ratio of the allowable output deviation to the maximum output deviation resulting from the allocation of the computed allowable parameter deviations, and hence to multiply the parameter deviations by the scaling factor.
5.2.8 **Subroutine DEVMAX**

This routine identifies the maximum of an array, and is called from CORFAC to identify the maximum output deviation over the cycle of motion of the mechanism.

5.2.9 **Subroutine CHECK**

It was mentioned in Chapter III section 3.2.5, that the allowable parameter deviations computed in the first instance with partial derivatives obtained using assumed numerical differentiation steps of the order of manufacturing tolerances are recomputed a second time after replacing the assumed steps with the deviations computed in the first instance. This routine is called from MAIN to do the replacements.

5.2.10 **Subroutine ORDER**

The procedure for evaluating tolerances and clearances from the parameter deviations requires, as described in Chapter IV, that the arc-length parameter deviations be arranged in an ascending order. For this purpose MAIN calls this routine prior to calling RESULT.

5.2.11 **Subroutine RESULT**

This routine is called from MAIN to determine the arc-length and arc angle tolerances and joint clearances from the allowable parameter deviations. To do so the routine implements the tolerance and clearance allocation steps (ii) to (v) set out in section 4.4 Chapter IV. For every arc encountered a check is made as to whether the clearances in the joints at the ends of the arc
have been determined in a preceding step, and then the
tolerance on the arc and the undetermined clearance(s) are
computed accordingly using the relationships given in Chapter
IV. If the arc has non-identical common arc(s), the joint at
which the arcs intersect is identified. Considering the arcs
as vectors pointing in the direction in which they are traversed
in the respective loops, there are four possibilities: (1) the
heads of the two vectors may meet at the common joint, (2) the
tails may meet at the common joint, (3) the head of the first
with the tail of the second, and (4) the tail of the first with
the head of the second. Hence the arc-angle tolerance and the
associated clearances are computed.

After determining all the tolerances and clearances
the routine prints out the results in tabular form.

5.2.12 Subroutine JSBSCR

A joint in a linkage is identified by three numbers,
the numbers of the arcs connected by the joint and the number
of the loop in which the arcs are traversed. Whenever a
parameter is encountered in RESULT, JSBSCR is called to deter-
mine the above mentioned identification numbers for the joint
associated with the parameter. The clearance in a joint has
the same identification numbers as the joint.

5.2.13 Subroutine TERNRY

This routine is called from routine RESULT whenever a
non-identical common arc is encountered. This routine then
determines all the other arcs which are non-identically common
with the one encountered by RESULT and their arc angles. To do this the routine uses the identification arrays set up by routine MAIN for the non-identical common arcs.

5.3 PROGRAM PSODPLOTS

This program was written to produce graph plots of parameter sensitivities and output deviation against input position. It comprises a MAIN routine and five subroutines. A flow chart for the program is shown in Fig. 5.2 and Appendix IC gives the listing of the program. The following sections give a description of the various routines and the operation of the program.

5.3.1 Routine MAIN

This routine reads the input data and plots the graphs. The input data, which is produced by the preceding program TOCALM, consists of an array of crank input positions and corresponding output deviations and parameter sensitivities. To draw the graphs MAIN calls appropriate routines from a graph plotting library called GHOST (GraphHical Output SysTem) which comprises a library of a large number of routines to draw lines, curves, characters, etc.

5.3.2 Subroutine SETPLS

This routine is called from MAIN and in turn it calls appropriate GHOST routines to draw axes for plotting the deviation bands of the mechanism output. The routine also writes the title of the plot and labels the axes.
5.3.3 Subroutine PAXES

This routine is called from MAIN and in turn it calls appropriate GHOST routines to draw axes for plotting the parameter sensitivities against crank input. In addition it writes the title for the plot and labels the axes.

5.3.4 Subroutine YSCALE

This routine is called from MAIN to determine the vertical scale for the parameter sensitivity plots. It identifies the maximum of the parameter sensitivity arrays and computes the vertical scale accordingly.

5.3.5 Subroutines SYMKEY and SYMBKY

These routines are called from MAIN to write a reference key for the parameter sensitivity plots. The curves corresponding to the parameters are plotted using a different symbol for each parameter. These routines identify the symbols with the corresponding parameters and write the key. SYMKEY is for arc-length parameters and SYMBKY for arc-angle parameters.
CHAPTER SIX

TOLERANCE AND CLEARANCE ALLOCATION:
APPLICATION TO EXAMPLES
6.1 INTRODUCTION

To demonstrate the applicability of the method of tolerance and clearance analysis developed in the preceding chapters to a wide range of planar linkage mechanisms and for purposes of comparison with relevant published work, the following mechanisms were selected.

(i) Four-Bar Sine Function Generator
(ii) Slider-Crank Mechanism
(iii) Four-Bar Motor Cycle Rear. Suspension
(iv) Six-Bar Sine Function Generator
(v) Eight-Bar Straight Line Generator
(vi) Ten-Bar Textile Needle Mechanism

6.2 FOUR-BAR SINE FUNCTION GENERATOR

The reason for selecting this mechanism for analysis is to compare the results of the present method with those of Dhande & Chakraborty [24], and Chakraborty [26]. Garrett and Hall [16] also used this mechanism in their investigation, however, as pointed out in Chapter II, they studied the deviation in output due to arbitrarily specified tolerances and clearances.

The mechanism is shown schematically in Fig. 6.1, with the arc length and arc angle parameters indicated. Table 6.1 shows the results of the analysis printed out by the computer program TOCALM, and Figs. 6.2 to 6.3 show the graphs plotted by the program PSODPLOTS. Figs. 6.2a and 6.2b show the variation of the output sensitivity to parameter deviation (i.e. the partial...
derivative of the output with respect to each parameter) with input position. The sensitivities to the arc length parameters are approximately of the same magnitude and their maxima coincide around input position $\theta = 65^\circ$. The sensitivity to the output arc-angle $\gamma_o$ is, as expected, constant and equal to unity, whereas the sensitivity to the input crank reference position, $\gamma_c$, varies greatly with input position.

Fig. 6.3 gives the variation of the output deviation with input position, when the tolerances and clearances in Table 6.1 are allocated to the mechanism. This, in fact, represents the limits within which would lie the deviations of 99.7 per cent (assuming 3σ tolerances) of mechanisms randomly assembled from parts with the above tolerances. When this band is wrapped around the structural error it results in what Garrett and Hall [6] termed the 'mobility band'.

In Table 6.2 the results are compared with those of the references mentioned above. The column labelled 'without cost optimization' was obtained when the effect of cost was not considered and the parameter deviations were assumed to contribute equally to the output deviation, see chapter three section 3.2.3, while the column labelled 'with cost optimization' refers to the results for optimum cost as derived in section 3.2.6 and incorporated in the program TOCALM. The cost coefficients, $B_i$, were chosen here arbitrarily. (In practice these should be obtained from cost tolerance data.)

The arc length tolerances for the case 'without cost optimization' are approximately the same as those obtained by
the quoted references; so are the clearances approximately equal to those of the second reference but equal to half of those of the first reference. Although the author of the second reference was also a co-author of the first and his work is an extension and improvement of that in the first reference, however he did not give any reasons for the difference in the results.

For the cost optimization, the coefficients \( B_i \) were chosen to be proportional to the squares of the arc lengths and as a result the tolerances are seen to have been redistributed making the tolerances on the longer arcs higher and vice versa.

A note worth mentioning is the fact that the quoted references did not account for the input reference angle, \( \gamma_c \), and the output arc angle, \( \gamma_o \), parameters. This is perhaps the reason for the tolerances obtained here being slightly smaller.

### 6.3 SLIDER-CRANK MECHANISM

The slider-crank mechanism is the most widely used linkage mechanism. It was selected as an example here to show that, despite the limitation sited in section 3.1, the program can handle linkages with sliding joints. The limitation referred to concerns the fact that the clearance in a sliding joint allows angular rotation of the sliding link relative to its guide in addition to the translational motion (see Fig. 3.1). The present program accounts for the translational motion only. However, since for most slider-crank mechanisms the coupler/
slider joint always remains within the range of the guide (Fig. 3.2), the results obtained here are useful.

Fig. 6.4 shows the mechanism schematically modelled in a form to suit the topological description used in the input data for the program.

The plots of the output sensitivity to changes in the various parameters are shown in Figs. 6.5a and 6.5b. The sensitivity to the connecting rod \((a_{2,1})\) varies very little through the input cycle while the sensitivities to the other parameters are cyclic. For the crank \((a_{1,1})\) the maxima are at \(0^\circ\) and \(180^\circ\) of the input position, while for the fixed arc \((a_{4,1})\) and the input reference angle \((\gamma_c)\) the maxima are at \(90^\circ\) and \(270^\circ\). Since here arc, \(a_{4,1}\) has zero length, the allowable deviation in this link is shared by the clearances and no tolerance is allocated to the arc length as the print out of the results Table 6.3 shows.

Fig. 6.6 shows the band within which the output deviation will lie due to the allocation of the tolerances and clearances shown in Table 6.3. The positions of maximum deviations coincide with the maximum sensitivity locations for the input reference, \(\gamma_c\), and the fixed arc, \(a_{4,1}\), i.e. \(\theta = 90^\circ \) & \(270^\circ\) rather than with that of the crank, arc \(a_{1,1}\). This is due to the relative size of the maximum sensitivities and also the cost coefficients, \(B_i\), used which shift the emphasis. Note that the comparison between the sensitivity to the arc lengths (mm/mm) and the sensitivity to the input reference (mm/rad.) is not a direct one.
6.4 FOUR-BAR MOTOR CYCLE REAR SUSPENSION

This linkage was synthesized by Oldham and Fawcett [30] as an alternative to the conventional suspension such that a constant distance is maintained between the gearbox output sprocket and the rear wheel sprocket. The linkage is shown schematically in Fig. 6.7. The coupler point W corresponds to the axis of the rear wheel. It generates a circular path with centre at S which corresponds to the gearbox output axis.

For the purpose of analysis of the linkage, link \( a_1 \) is taken as the input link and point \( W \) is the output point. The output is measured in polar coordinates. With reference to Fig. 6.7, \( \phi_R \) is the polar radius and \( \phi_A \) is the polar angle. The results of the tolerance and clearance analysis are given in Table 6.4 and Figs. 6.8 - 6.9. The table gives the tolerances and clearances allocated for the specified tolerances of the output in the polar radius and polar angle.

Figs. 6.8a - 6.8c give the output sensitivities to parameter deviations plotted against the input position. In the above reference the authors calculated the variation in the centre distance (i.e. polar radius) when each of the moving links \( (a_{1,1}, a_{2,1}, a_{3,1}) \) is shortened or lengthened by 1 mm. They found the r.m.s. error 0.74 and 0.46 mm for \( a_{1,1} \), 0.92 and 0.54 for \( a_{2,1} \) and 0.36 and 0.58 for \( a_{3,1} \). Compared with Fig. 6.8a(i) there are large differences except for \( a_{1,1} \) the difference is relatively smaller. The differences are due to the size of the parameter deviation used to calculate the sensitivity. Whereas in the above reference a parameter
deviation equal to 1 mm was used, here the parameter deviations are equal to the tolerances allocated which are (from Table 6.4) 0.089 mm for $a_{1,1}$, 0.425 mm for $a_{2,1}$ and 0.183 mm for $a_{3,1}$.

The output deviation in the polar radius varies from a minimum of 0.23 mm at the initial input position to a maximum of 1.0 mm at the final input position. Judging from the sensitivity curves it is evident that it is influenced most by the tolerances allocated to the output arc angle, $\gamma_0$, and the origin arc angle $\gamma_{g}$.

6.5 SIX-BAR SINE FUNCTION GENERATOR

This mechanism, shown schematically in Fig. 6.10, was analysed by the Design Unit [34] and was chosen for analysis here to represent another class of mechanisms and to compare results where possible. The function generated is $\phi = k \sin \theta$, where $k$ is a constant, $0 \leq \theta \leq 180^0$.

Figs. 6.11 show the output sensitivity curves. As expected the sensitivity for the crank, $a_{1,1}$, varies symmetrically with the input position with maximum around $\theta = 90^0$ (Fig. 6.11a). In Fig. 6.11b, arc $a_{4,2}$, which is identical common with $a_{1,1}$, gives an approximately similar curve, but the value is different since in Fig. 6.11 it is treated as an arc in the second loop. The sensitivity curves for $a_{3,1}$ and $a_{3,2}$ are similar (both being approximately constant and of the same magnitude), as would be judged intuitively due to their orientations. The sensitivity curves for $a_{2,2}$ and $a_{4,2}$ are almost identical whereas that for $a_{2,1}$ is a mirror image of
the first two. The sensitivities to the fixed arcs $a_{4,1}$ and $a_{5,2}$ are also similar in shape and magnitude, perhaps due to the symmetrical locations of the fixed pivots. The sensitivities to the arc angle $\gamma_{2,2}$ and the output arc angle $\gamma_0$ are constant throughout the input positions as expected, while for the input reference, $\gamma_c$, the curve is symmetrical with a minimum at $\theta = 90^\circ$.

Fig. 6.12 shows the output deviation band when the tolerances and clearances given in Table 6.5 are allocated to the mechanism.

The above mentioned reference gives plots of the root mean square (r.m.s.) of output error against parameter deviation. The curves are steepest for arcs $a_{1,1}'$, $a_{4,2}$ and $a_{2,2}'$, and arc-angles $\gamma_{5,2}$ and $\gamma_{2,2}$ ($\gamma_0$ not given). The least steep is that for $\gamma_c$. There is a general similarity in the results, but a direct comparison is not possible. The reference above quotes $a_{3,1}$ and $a_{3,2}$ as the least critical arc lengths, where here, as noted earlier, their effect on the output is obviously large. The reason is that in the above reference the errors which may be eliminated by adjusting the reference angles were not accounted for, i.e. 'the reference angles were adjusted to obtain the minimum error'.

6.6 EIGHT-BAR STRAIGHT LINE GENERATOR

This mechanism was selected to represent the tolerance analysis of an eight-bar linkage. Table 6.6 gives the printout of the results. Since the mechanism is symmetrical, see Fig. 6.13, the
tolerances allocated to the corresponding links are the same (cf. \(a_{2,1} \& a_{2,2}; a_{3,1} \& a_{3,2}\)). The same is true for the arcs \(a_{3,3}\) and \(a_{3,4}\), however because they lie in the same loop and have a common joint, and since the clearance is included with the deviation of one of the arcs having the common joint, the tolerances allocated are therefore different. In such situations, to maintain symmetric tolerances, the designer may reallocate the tolerances such that half the clearance is included with each arc.

This symmetry is also expressed by the sensitivity curves, c.f. sensitivity to \(a_{2,1}\) and \(a_{2,2}\) in Figs. 6.14a(i) and 6.14b(i) respectively for the x-direction and Figs. 6.14a(ii) and 6.14b(ii) for the y-direction, and similarly for the other corresponding arcs that are symmetrical (viz \(a_{3,1}\) and \(a_{3,2}\) in the Figs. referred to above, and \(a_{3,3}\) and \(a_{3,4}\) in Figs. 6.14c(i) for the x-direction and Fig. 6.14c(ii) for the y-direction).

Fig. 6.14d(i) could be misleading until one realizes that the vertical ordinates are of the order of \(10^{-11}\), i.e. effectively zero, as they are beyond the accuracy of the computer (\(\approx 10^{-7}\) in single precision). As would be expected the mechanical error in the x-direction is independent of the crank (input) reference angle, \(\gamma_c\). But in the y-direction the effect of \(\gamma_c\) is substantial as is evident from Fig. 6.14d(ii).

Figs 6.14(i) and 6.15(ii) show the output deviation bands, in the x- and y-directions respectively, due to the allocation of the tolerances and clearances determined in the analysis (Table 6.6). Due to the symmetry of the mechanism,
referred to above, the band widths are symmetrical about the mean input position. It is evident that the mechanism output in the y-direction is much more sensitive to parameter deviations than is the output in the x-direction. This may be an advantage where the straightness of the path generated is paramount.

6.7 TEN-BAR NEEDLE MECHANISM

This is a mechanism from the textile industry and was used by Oldham [29] as a case study for dimensional optimization. It is used here to further illustrate the application of the present method of tolerance and clearance analysis to complex linkages. The mechanism is shown schematically in Fig. 3.3 and Table 6.7 gives the computer print out of the results of the analysis. Figs. 6.16a to 6.16b show the sensitivity curves. The sensitivities for some of the parameters vary more sharply than others with input position, e.g. for $a_{1,2}$ the sensitivity varies from a maximum of 0.012 rad/mm to a minimum of almost zero whereas that for $a_{4,4}$ remains nearly constant throughout the cycle. The reason is that $a_{1,2}$ is the crank which rotates through 360° while $a_{4,4}$ changes orientation only slightly throughout the cycle.

Fig. 6.17 shows the output deviation band due to the allocation of the tolerances and clearances determined. Comparing this with that of, say the four-bar sine function generator, Fig. 6.3, it can be seen that it has a good feature, i.e. the band width does not vary considerably over the cycle of
the mechanism motion. This is due to the fact that unlike the case of the four-bar, the worst sensitivities do not coincide at or near one input position, c.f. Fig. 6.2a and Figs. 6.16 (a-h). This may be used as a design criterion at the synthesis stage of a mechanism.

6.8 COMMENTS

The examples presented give a guide to the scope of applicability of the method. The program handles planar mechanisms with rotary input but with four types of output, viz. rotary (examples (i), (iv) and (vi)), sliding (example (ii)), linear measured in polar coordinates (example (iii)), and linear measured in cartesian coordinates (example (v)).

The graphical output gives a very useful picture about the performance of the mechanism and about the critical parameter dimensions. Based on this information the designer may judge whether the mechanism is satisfactory or needs to be revised.

The print-outs of the results also give the execution times for the tolerance analysis. Of course the more complex the mechanism the higher the time. If the output is measured by one coordinate, i.e. rotary or sliding output, the time will be one half of that when the output is measured by two coordinates, i.e. polar or cartesian coordinates of a point. Another factor is of course the number of input positions for which the analysis is made.
PART II

MAINTAINING CONTACT IN JOINTS
CHAPTER SEVEN

MAINTAINING CONTACT IN JOINTS:
LITERATURE SURVEY
7.1 INTRODUCTION

The dynamic effects of clearances in the joints of a mechanism have received a growing attention from investigators. Various analytical approaches have been used to predict the response of mechanisms with clearances and a number of experimental investigations have been carried out on joint models and on mechanisms with clearance in one or more of their joints. A few investigators paid particular attention to eliminating impact in the joints through satisfying conditions for maintaining contact. In the following sections these various investigations are reviewed.

7.2 ANALYTICAL INVESTIGATIONS

In the analytical investigations two distinct methods are apparent. Either the response of an idealised one dimensional model is investigated or a specific mechanism is simulated by an analytical model. Goodman [41] replaces the actual system by an equivalent 'box-car diagram' analogous to a train of box-cars, determines the response of the equivalent system and correlates it to the actual system. The box-cars are idealised rigid bodies separated by springs and dashpots. The motion following impact is found on a piece-wise basis.

A two mass model separated by spring and dashpot similar to the box-car diagram is used by Dubowsky and Freudenstein [42]. Response of the model, termed an impact-pair, when subjected to vibrational inputs is formulated using the describing function technique. Results indicate that impact forces increase
with clearances. Winfrey [45] also uses an analytical simulation for a one dimensional system with clearances using a cam-driven valve train and an impact damper as examples.

Earles and Wu [46] use Lagrangian equations to simulate a four bar mechanism with a predominant clearance in the coupler follower joint. The clearance is replaced by a massless 'clearance-link' coincident with the joint force direction. The analysis is carried out up to the point of contact loss. Dubowsky [47] gives an analytical simulation to determine the response of a slider-crank-mechanism with clearance at the crank-coupler joint. The results were found to be similar to that predicted by the 'impact-pair' model of reference [42]. Similar results were confirmed by Dubowsky [48].

A different approach which uses momentum exchange to determine impulsive reactions is used by Townsend and Mansour [51, 52] and applied to a four-bar crank rocker with clearance in the coupler-rocker joint. The results give impact spectra and agree with those of other methods. Impact intensity is found to increase with clearance size and speed of input.

To investigate the effect of link elasticity on the joint impact loads, Dubowsky and Gardner [53] studied the response of an "impact beam model" subjected to dynamic excitation perpendicular to the longitudinal axis. It was found that link flexibility reduces the impact forces in the bearings. In a later paper [57] they used Lagrangian formulation to develop dynamic equations for a general elastic clearance system in which link displacements relative to the nominal
positions described by the no-clearance analysis were used to write kinetic and potential energy expressions. The analysis was applied to a scotch yoke and the results agreed qualitatively with that predicted by the impact beam model.

Townsend and Mansour [55] used a functional analysis approach to analyse the effects of clearance at the coupler-follower joint of a four-bar mechanism. The time between successive impacts was estimated. Meidema and Mansour [56] used a momentum exchange approach to develop a three mode model: free flight, impact, and 'following' or contact maintained mode. It was found that the zones of contact were compatible with that predicted by the no-clearance analysis.

Yet another approach which employs a vector-network method was used by Rogers and Andrews [58] to simulate a slider crank mechanism. In the analysis the system was treated as rigid bodies interconnected by rotational and translational springs and dashpots and bearing elements. The effects of lubrication and varying stiffness and damping were investigated.

Bahgat et al [64] developed a mathematical model of a four-bar mechanism with clearances in the frame-crank, crank-coupler and coupler-rocker joints. The links were considered rigid bodies and contact modes were detected by iteration according to the inequalities of input torque and pin forces. The 'clearance links' were aligned with the directions of the respective pin forces and the resulting interdependent kinematic and kinetic equations were solved simultaneously to determine
the input torques, pin forces and predict separation occurrences.

Haines [70], adopting simplifying assumptions based on deductions from his survey [69], developed equations of motion for a revolute joint using the principle of virtual work. Conditions for loss of contact were hence derived and embodied in a design chart which is in the form of a contour map defining thresholds of contact loss.

7.3 EXPERIMENTAL INVESTIGATIONS

The experimental investigations into the effects of bearing clearances ranged from the measurement of response of mechanisms with clearances in one or more of the joints substantiating analytical models to the development and testing of simple empirical relationships for predicting contact loss in a bearing. Fawcett and Burdess [43] investigated the bearing force in the coupler-rocker joint of a four-bar mechanisms with a predominant clearance in the said joint. The positions of impact correlated to that predicted by no-clearance analysis. The results also showed that impact force increased with clearance size and decreased with compliance of the bearing bush.

Earles and Wu [50, 59-61] used experimental investigations on a mechanism with a clearance in the coupler-rocker joint to evolve and substantiate empirical relationships for predicting occurrence of contact loss and for estimating impact magnitudes. The validity of the empirical relationships was further confirmed by Grant and Fawcett [62], Grant [65], and

Dubowsky and Young [54] investigated a simple pin connection subjected to sinusoidal input motion, a set up similar to the analytical model known as the 'impact pair' devised by Dubowsky and Freudenstein [42], and found that the experimental results confirmed the behaviour predicted by the analytical model. Such agreement is also reported by Dubowsky and Moening [63] who tested a scotch yoke mechanism and compared the results with that of the analytical model of Dubowsky and Gardner [57].

7.4 MAINTAINING CONTACT

Few investigators have paid particular attention to satisfy conditions for maintaining contact, since if this may be achieved there will be no need for the complex and lengthy analysis to determine the response of systems with clearances beyond the point of contact loss. Fawcett and Burdess [44] suggested that this may be achieved by either of two methods, viz. mass redistribution or spring loading, such that the polar force diagram shape is changed making its contour as far removed as possible from the zero force point. Fawcett [49] described a design of bearing along the principle of force-form closure whereby the bearing is spring loaded in a direction determined from a no-clearance analysis such that the polar force contour is removed far from the zero point.

Earles and Wu [60] suggested modifying the design such that the empirical criterion for maintaining contact
\( \dot{\gamma}/R < 1 \) (where \( R \) is the minimum joint force measured in Newtons and \( \dot{\gamma} \) is the corresponding rate of change of direction of \( R \) measured in radians per second) is satisfied.

7.5 PRESENT INVESTIGATION

In the present study an attempt is made to maintain contact in the bearings of a four-bar mechanism by addition of masses to the links, i.e. by mass redistribution. An objective function is developed such that minimizing it leads to approaching the conditions for maintaining contact.
CHAPTER EIGHT

MAINTAINING CONTACT IN LINKAGE JOINTS:
THEORY AND ANALYSIS
8.1 INTRODUCTION

For contact to be maintained between the pairing elements in a joint of a linkage mechanism, intuition suggests that a force must press the elements against each other. However, according to previous investigations [50, 61], this condition alone will not insure maintaining contact, and another condition, that the force between the elements must not change direction rapidly, has also to be satisfied. These two conditions depend among other factors, on the distribution of the masses on the moving elements of a mechanism. In the following analysis an attempt is made to optimize the mass distribution of a plane four-bar linkage with revolute joints to satisfy the above conditions as closely as possible.

Mass redistribution is also used for balancing purposes, i.e. eliminating the shaking force and shaking moment transmitted to the frame of a mechanism. Hence, using the same method for a different purpose will probably be at the expense of the other. However, this is the designer's problem to decide which one to sacrifice in a particular case.

8.2 OBJECTIVE FUNCTION

To optimize the mass distribution of a mechanism an objective function must be derived such that when this objective function is made a minimum (or maximum, as the case may be), then the mass distribution is optimum. Our objective here is to maintain contact at the joints of a four-bar linkage. Intuition suggests that the ideal situation for maintaining
contact between the elements of a revolute joint is the case where a bar rotates in a horizontal plane about a pin which fits in a hole at one end of the bar, see Fig. 8.1. In such a case, with the bar rotating at a constant speed, the force at the joint acts along the axis of the bar. It has a constant magnitude and rotates at a constant rate. Hence, this ideal is the objective to be achieved for the forces in the joints of the mechanism and the objective function will now be formulated accordingly.

Expressions for the forces at the joints of a four-bar linkage are given in Appendix IIB. For clarity these forces are represented graphically in Fig. 8.2 where the external forces have been excluded. In the following analysis the external forces will be assumed negligible in comparison to the inertia forces. The input crank will be assumed to rotate at a constant speed, \( \dot{\theta}_1 \).

To satisfy the condition of rotating at constant rates, the joint forces will be required to rotate at the same rate as the input crank but may have a phase shift from the crank direction. This requirement is in order since the vector heads of these forces trace a closed loop when the crank rotates through one revolution. Then the direction \( \gamma_{ij} \) of the force vector at any joint may be expressed as

\[
\gamma_{ij} = \theta_1 + \zeta_{ij} \quad 8.1
\]

where \( i = 1, 2, 3, 4 \)

\( j = 2, 3, 4, 1 \)

\( \zeta_{ij} = \text{phase shift} \)
Hence the cartesian coordinates of the force vectors may be expressed as

\[ F_{ijx} = F_{ij} \cos(\theta_1 + \varsigma_{ij}) \]  

\[ F_{ijy} = F_{ij} \sin(\theta_1 + \varsigma_{ij}) \]  

Eliminating \( F_{ij} \) from equations 8.2 above gives

\[ F_{ijx} \sin(\theta_1 + \varsigma_{ij}) - F_{ijy} \cos(\theta_1 + \varsigma_{ij}) = 0 \]  

If the parameters of \( F_{ijx} \) and \( F_{ijy} \) (see Appendix IIB) and the phase shift \( \varsigma_{ij} \) are adjusted such that equation 8.3 is satisfied throughout the cycle of the linkage, then the condition that the force vector rotates at a constant rate will be satisfied.

The other condition requires that the magnitude of the force remains constant. Taking into account the empirical relationship of Earles and Wu [50] for maintaining contact, i.e. that \( \dot{\gamma}/R < 1 \) - where \( R \) is the minimum reaction force in a joint obtained by no clearance analysis (measured in Newtons) and \( \dot{\gamma} \) is the corresponding angular velocity (in rad/sec) of the force vector \( R \), the magnitude of the required constant force may be deduced. Allowing for the inevitable variations in the magnitude of the force and the rate at which it rotates we shall write the above relationship as

\[ \frac{\dot{\gamma}_1}{R_{ij}} = 0.8 \]  

8.4
where \( R_{ij} \) = mean value of \( F_{ij} \), i.e. making an allowance for a variation of 20% to the limit \( \gamma/R < 1 \). Hence the second condition will be satisfied if

\[
F_{ij} - 1.25\dot{\theta}_1 = 0
\]  

8.5

is satisfied throughout the cycle of motion of the mechanism.

The expressions on the left hand sides of equations 8.3 and 8.5 form the elements of the objective function. For an optimum, these expressions must have minimum absolute values for all the joints; summated throughout the cycle, such that absolute values are considered, the sum of squares will be used. Hence the objective function may be expressed in the form

\[
f = \sum_{r=1}^{n} \left[ F_{12x} \sin(\theta_1 + \xi_{12}) - F_{12y} \cos(\theta_1 + \xi_{12}) \right]^2_r + \left[ F_{12} - 1.25\dot{\theta}_1 \right]^2_r
\]

\[
+ \left[ F_{23x} \sin(\theta_1 + \xi_{23}) - F_{23y} \cos(\theta_1 + \xi_{23}) \right]^2_r + \left[ F_{23} - 1.25\dot{\theta}_1 \right]^2_r
\]

\[
+ \left[ F_{43x} \sin(\theta_1 + \xi_{43}) - F_{43y} \cos(\theta_1 + \xi_{43}) \right]^2_r + \left[ F_{43} - 1.25\dot{\theta}_1 \right]^2_r
\]

\[
+ \left[ F_{41x} \sin(\theta_1 + \xi_{41}) - F_{41y} \cos(\theta_1 + \xi_{41}) \right]^2_r + \left[ F_{41} - 1.25\dot{\theta}_1 \right]^2_r
\]

8.6

where \( n \) = no. of positions.
8.3 OPTIMIZATION PARAMETERS

Since the aim is an optimum mass distribution, the parameters of optimization are those parameters which define the mass distribution. For each link these parameters are: the mass, the two coordinates which define the position of the centre of mass, and the moment of inertia. These mass distribution parameters - three for the crank (since joint forces are independent of the inertia of the crank, see Appendix IIB), and four per each of the coupler and follower - plus the four phase shift angles ($\tau_{ij}$) defining the directions of the joint forces relative to the input arc position - make a total of fifteen optimization parameters.

The mass distribution parameters may be taken as the parameters of the additional masses required to make the distribution an optimum rather than those for the total mass of a link. Fig. 8.3 shows an additional mass $m_*$ with coordinates of its mass centre $\rho_*$ and $\lambda_*$ added on to a link of original mass $m_0$ and mass centre coordinates $\rho_0$ and $\lambda_0$. The mass centre of the total mass is defined by the coordinates $\rho$ and $\lambda$.

Let $k_0$, $k_*$ and $k$ define the radii of gyration about the origin of the original mass, the additional mass and the total mass respectively. The relations between the corresponding quantities follows:

\[
\text{Mass: } \quad m = m_0 + m_* \quad \text{8.7}
\]
\[
\text{Inertia: } \quad mk^2 = m_0 k_0^2 + m_* k_*^2 \quad \text{8.8}
\]
Centre of mass coordinates:

With reference to Fig. 8.3, let $\bar{x}$ and $\bar{y}$ be the components of $\rho$ relative to the coordinate axes $x-y$. Taking moments of mass about the respective axes gives:

$$\bar{x} = \frac{m_0 \rho_0 \cos \lambda_0 + m_\star \rho_\star \cos \lambda_\star}{m}$$

$$\bar{y} = \frac{m_0 \rho_0 \sin \lambda_0 + m_\star \rho_\star \sin \lambda_\star}{m}$$

Hence

Radius: $\rho = \sqrt{\bar{x}^2 + \bar{y}^2} = \frac{1}{m} \sqrt{m_0^2 \rho_0^2 + m_\star^2 \rho_\star^2 + 2m_0 \rho_0 m_\star \rho_\star \cos(\lambda_\star - \lambda_0)}$  \hspace{1cm} (8.9)

Angle: $\lambda = \tan^{-1} \left( \frac{\bar{y}}{\bar{x}} \right) = \tan^{-1} \left( \frac{m_0 \rho_0 \sin \lambda_0 + m_\star \rho_\star \sin \lambda_\star}{m_0 \rho_0 \cos \lambda_0 + m_\star \rho_\star \cos \lambda_\star} \right)$  \hspace{1cm} (8.10)

8.4 BOUNDARY LIMITS ON OPTIMIZATION PARAMETERS

The angular parameters, i.e. orientations, $\lambda_\star$, of mass centres for the additional masses on the moving links and the phase shifts, $\zeta_{ij}$, of the joint force directions, obviously need not be bounded. However the remaining parameters need to have boundary limits imposed upon them.

The additional masses, $m_\star$, on each of the moving links, may not be allowed to become negative nor exceed a specified upper limit. This upper limit mainly depends upon allowable forces and available space. Denoting the upper limit by $m_u$,...
the boundaries on $m_*$ may be expressed by

$$0 < m_* < m_u$$  \hspace{1cm} 8.11$$

The centres of mass radii, $\rho_*$, for the additional masses need also not to exceed an absolute upper limit determined by the available space among other factors. If the upper limit is denoted by $\rho_u$, then

$$-\rho_u < \rho_* < \rho_u$$  \hspace{1cm} 8.12$$

The lower limit $-\rho_u$ is of course the same as the upper limit with an offset of $180^\circ$. It may be argued that since $\lambda_*$ is not bounded, setting the bounds of $\rho_*$ as $0 < \rho_* < \rho_u$ would have been sufficient. However, it was found that setting the bounds as in 8.12 provided an additional freedom during the optimization and a safeguard against being trapped by a fictitious bound.

The radii of gyration, $k_*$, for the additional masses about the local origins on the links may be expressed in the form

$$k_* = \sqrt{\rho_*^2 + k_{G*}^2}$$  \hspace{1cm} 8.13$$

where $k_{G*}$ = radius of gyration of the additional mass about its own centre of mass.
The limits on $k_{G*}$ are determined by the allowable dimensions of the additional mass. If $m_*$ is zero $k_{G*}$ is of course immaterial. But with $m_*$ non-zero what will the lower limit on $k_{G*}$ be? This question was answered by Walker [66]. If the additional mass is attached to the link via a frictionless bearing at the centre of mass of the additional mass, then the moment of inertia of the additional mass about its centre of mass is eliminated. Hence, the limits on $k_{G*}$ may be expressed by

$$0 \leq k_{G*} \leq k_{Gu}$$

where $k_{Gu}$ is the upper limit.
CHAPTER NINE

MAINTAINING CONTACT IN LINKAGE JOINTS:
COMPUTER PROGRAMS
9.1 INTRODUCTION

Two programs are described in this chapter: the first deals with the minimization of the objective function developed in the preceding Chapter VIII, and the second is a graph plotting program for plotting the joint forces. The first program, CONTACT, comprises a MAIN routine and besides the minimization routine E04JBF from the NAG library, subroutines FUNCT, MONIT and RESULT. The NAG library is a library of computer routines which incorporate numerical algorithms for solution of problems in various subject areas. The library has been compiled by the Numerical Algorithm Group, U.K.

9.2 SELECTION OF MINIMIZATION ROUTINE

In search of a suitable optimization routine the NAG FORTRAN Library document on 'Minimizing or Maximizing a Function' [2] was consulted. The NAG Library contains a set of routines to solve a variety of problems. One set is concerned with optimization problems with each routine implementing an algorithm suitable for a certain category of problems. Each category is defined by the property of the function to be minimized—i.e. whether linear, non-linear, quadratic, or sum of squares of linear or non-linear functions—and the restrictions on the values of the optimization variables (or parameters)—i.e. constrained (simple bounds, linear or non-linear) or unconstrained.

The choice of routine depends on several factors. The category of the problem and the level of derivative information
supplied are the main factors. The function to be minimized in the present problem is given by expression 8.6, Chapter VIII. It is a summation of squares of non-linear functions. The restrictions on the optimization parameters are simple lower and upper bounds (see section 8.4 Chapter VIII). The first and second derivatives are too complicated to determine analytically. Accordingly the Library routine E04JBF was selected for the minimization of the function. A description of this routine is given in section 9.3.2.

9.3 PROGRAM CONTACT

A flow chart of this program is given in Fig. 9.1. The component routines of the program are represented by block units. The connecting paths with arrow heads indicate the flow of the program. A listing of the program is given in Appendix IIC, and the component routines are described in the following sections.

9.3.1 Routine Main

This is the controlling unit of the program. It reads in the input data which consists of the dimensional parameters of the four bar linkage, and the initial or starting values of the optimization variables and their lower and upper bounds. It sets the parameters of the optimization routine E04JBF and prior to calling this routine, it calls Library routine E04HB to supply suitable steplengths for making difference approximations to the partial derivatives of the objective
function. After a successful return from the optimization routine MAIN calls routine RESULT to print out the results.

9.3.2 Library Routine E04JBF

As described in the NAG Library document [71] this routine incorporates a quasi-Newton algorithm for finding a minimum of several variables which may be either unconstrained or subject to fixed upper and/or lower bounds. It calls the supplied subroutine FUNCT to evaluate the objective function and calls a host of other library routines to evaluate first and second partial derivatives of the function with respect to the variables and implements the optimization. It also calls subroutine MONIT at a specified frequency to monitor the progress of the optimization process.

The essential feature of the algorithm used - as quoted in the routine document [71] - is that the Hessian matrix $G(k)$ (at iteration step 'k') for position $X(k)$ (where $X$ is the matrix of optimization variables) is used to define the search direction $p(k)$. A cholesky factorization based on $G(k)$ is computed to satisfy

$$L(k)D(k)L(k)^T = G(k) + E(k)$$

where $L(k)$ is a lower triangle matrix with unit diagonal elements, $D(k)$ is a diagonal matrix with strictly positive diagonal elements, and $E(k)$ is a diagonal matrix with non-negative diagonal elements. If $G(k)$ is sufficiently positive
definite, \( E(k) \) is the zero matrix. The search direction is then obtained by solving the linear system

\[
L(k) D(k) L(k)^T p(k) = -g(k)
\]

where \( g(k) \) is the gradient vector, i.e. vector of first partial derivatives of the objective function \( F(x(k)) \).

A sequence \( x(k) \) is then constructed satisfying

\[
x(k+1) = x(k) + \alpha(k) p(k)
\]

where \( \alpha(k) \) is a step length chosen such that

\[
F(x(k+1)) < F(x(k))
\]

\( x(k) \) is then replaced by \( x(k+1) \) and the process is continued until the convergence criteria are satisfied.

If any variable reaches a bound during the search, it is fixed and the number of 'free' variables is reduced for the next iteration. The components of the search direction corresponding to variables currently on a bound are set to zero.

For a feasible point \( \bar{x} \) to be a solution, the following conditions must be satisfied:

(i) \( |\bar{g}(\bar{x})| = 0 \)

(ii) \( \bar{g}(\bar{x}) \) is a positive definite
(iii) \( g_j(\mathbf{x}) < 0, \) \( x_j \) at the upper bound

\[ g_j(\mathbf{x}) > 0, \] \( x_j \) at the lower bound

where \( \mathbf{g}(\mathbf{x}) \) is the gradient with respect to the free variables, and \( \mathbf{G}(\mathbf{x}) \) is the Hessian matrix with respect to the free variables.

9.3.3 Subroutine FUNCT

This routine incorporates the equations given in Appendices IIA and IIB and the equation for the objective function given in Chapter VIII. It is called from the Library routines to compute the function value. The optimization variables which are adjusted by the Library routine at each iteration are incorporated into the linkage parameters as defined by equations 8.7 to 8.10 and 8.13 in Chapter VIII. This routine is also called from MAIN after the completion of the optimization to provide the joint forces and the final mass distribution.

9.3.4 Subroutine MONIT

This routine is supplied to monitor the progress of the optimization process. It is called from the Library routine E04JBF at specified intervals to print out:

(i) the value of the function

(ii) the number of function evaluations that has been made so far

(iii) the values of the optimization variables, the first derivatives of the function with respect
to the variables, and the status of the variables, i.e., whether free or at a bound,

(iv) the ratio of the largest and smallest elements of the matrix $D$ mentioned in section 9.3.2, which is a good estimate of the condition number of the projected Hessian matrix, and

(v) The Euclidean norm of the projected gradient vector.

The frequency at which MONIT is called is set by the user. The setting may be none, once at the end of the optimization run, or each time a certain number of iterations have been completed.

9.3.5 Subroutine RESULT

This routine is called from MAIN at the completion of optimization to print out the final values of the optimization variables and the resulting mass distribution of the moving links. It also writes into a computer file the joint forces corresponding to an array of crank input positions for subsequent plotting by program PINFORCE.

9.4 PROGRAM PINFORCE

This program was written to produce plots of the joint forces. It consists of a MAIN routine and a subroutine SKALE, and graph plotting routines from the Library file *GHOST. Fig. 9.2 gives a flow chart for the program and a listing of the program is given in Appendix IID.
Routine MAIN reads the data stored by the preceding program CONTACT which gives the cartesian coordinates of the joint forces corresponding to an array of input positions. For the plot at each joint MAIN calls SKALE to determine the scales of the plot to suit the extreme values of the joint force coordinates. MAIN then calls appropriate routines from *GHOST to produce the plot.
CHAPTER TEN

MAINTAINING CONTACT IN LINKAGE JOINTS:
APPLICATION TO EXAMPLES
10.1 INTRODUCTION

The method of optimizing mass distribution to maintain contact in the joints of four-bar linkages developed in the preceding Chapter VIII and incorporated into the computer program, Chapter IX, was applied to three examples:

1. a crank-rocker with a relatively poor transmission angle,
2. a crank-rocker with a better transmission angle, and
3. a drag-link.

The first example was chosen arbitrarily to test the validity of the method, but the other examples were selected to demonstrate the effect of (a) the transmission angle, and (b) a rotating follower as against a rocking follower. The results are presented in the following sections.

10.2 CRANK-ROCKER WITH RELATIVELY POOR TRANSMISSION ANGLE

This linkage was, as mentioned above, chosen arbitrarily, and it happened that its transmission angle - with extreme values of $\approx 29^0$ and $98^0$ - was relatively poor at the lower end. The parameters of this linkage are given in Table 10.1. The mass parameters are in accordance with the definitions in Fig. 8.3. Suffix 'o' refers to the original mass, i.e. before addition of mass to optimize the distribution, and 'x' refers to the added mass to achieve an optimised mass distribution. The moments of inertia $I_o$ and $I_x$ are about
the local origin on each link.

Table 10.2 gives the print out of the computer program CONTACT. It shows the initial values of the optimization variables and objective function, and the respective final values at the end of the optimization run. Figs. 10.1 and 10.2 give joint force plots produced by program PINFORCE. These are for the cases with the added mass parameters set to: (i) zero, and (ii) optimized values respectively. It is evident that the optimization has improved the joint forces both in magnitude and in the rate of rotation. This is especially true for the frame-crank and crank-coupler joints. Obviously this is due to the fact that they are the joints at the ends of the crank which rotates at a constant rate. However, at the other two joints the kinematic parameters of the mechanism did not allow much improvement. It must be noted that the optimization routine may not achieve a global minimum, but converges to the local minimum in the vicinity of the starting point (i.e. initial values of the optimization variables). Hence the choice of the starting point is very crucial though it is subject to trial and error.

10.3 CRANK-ROCKER WITH IMPROVED TRANSMISSION ANGLE

The frame arc of the preceding example was adjusted so as to give a linkage with better extreme values for the transmission angle. The extreme values of the transmission angle for this linkage are ±49° and 132° (c.f: 29° & 98° for the preceding). The linkage parameters are given in Table 10.3.
The results of the optimization run are shown in Table 10.4, giving the values of the optimization variables at the starting point and the final point.

Fig. 10.3 gives the joint forces when only the original masses of the links apply. The effect of transmission angle is evident even before optimization. Though the mass parameters are identical, the joint forces are very much improved with respect to variation in magnitude and rate of change of direction. The reason for this is explained by the equations for the forces (see equations IIB.4 in Appendix IIB) and also by the vector representation of the force components in Fig. 8.2, where it is seen that two components of the force vectors have $\sin \mu$, i.e. the sine of the transmission angle, in their denominators. Fig. 10.4 shows the joint forces after optimizing the mass distribution. The starting values for the optimization variables were the same as for the preceding example - c.f. Tables 10.2 and 10.4. Comparison of Fig. 10.4 with Fig. 10.2 for the preceding example shows that the result of optimization for the linkage with the better transmission angle is slightly better. This is especially true for the frame/crank and crank/coupler joints where the rate of rotation of the joint force is more uniform, c.f. around the points corresponding to $0^\circ$ crank angle. For the other two joints, though the response to the optimization is comparatively better than for the preceding example, however the optimization did not achieve the required result.

A comparison of the results print out, Tables 10.2
and 10.4, shows that for this example the function value reduced from 0.24539 to 0.18745 - a reduction of 0.05794 (23.6%), and for the preceding example from 0.27801 to 0.23297 - a reduction of 0.04504 (19.3%). The order of the actual function given in Chapter VIII equation 8.6 is $10^5$ times but had to be scaled down as required by the optimization routine: that the value is of the order of unity.

It is thus obvious that the optimization failed to reduce the objective function value substantially. This is due to the limitations in the problem itself and possibly in the formulation of the objective function. These limitations will be discussed in more detail in Chapter XI.

The function values given above again emphasize that improving the transmission angle has made the response of the problem to optimization slightly better.

10.4 DRAG-LINK

This linkage is an inversion of the crank rocker with the improved transmission angle, the crank and frame have interchanged roles. It was chosen here as an example because it was felt that in the case of the crank-rocker the fact that the follower does not rotate continuously may have hampered the optimization. The parameters of the linkage are given in Table 10.5, and the result of the optimization run is given in Table 10.6. Figs. 10.5 and 10.6 show the joint-force plots prior to and after the addition of masses to optimize the mass distribution respectively.
Comparing the force plots to optimization to the corresponding ones for the crank-rocker (c.f. Figs. 10.3 and 10.5), it is evident that the drag link has a more favourable joint force behaviour. This is especially so for the coupler/follower and follower/frame joints.

However the results of the optimization, though they have approached the objective a little further than in the previous examples, still fell short of producing satisfactory joint forces, for the coupler/follower and follower/frame joints. It is possible that a more favourable starting point may have produced a better result. Table 10.6 shows a reduction in the objective function value from 0.20688 to 0.17103, a difference of 0.03585 (17.3%). Though the minimum function value is smaller than for the preceding examples, however, the reduction achieved is also less. This again emphasizes that the optimization may have been trapped into a local minimum by an unfortunate choice of the starting values for the optimization variables.

10.5 COMMENTS

The results for the above examples show that mass distribution may be used as a tool for achieving joint force conditions for maintaining contact. However it is evident that it has several drawbacks. The magnitude of the force is increased by an order of three or more which means more wear in the bearings and possible failure. For the joints not associated with a continuously rotating link the geometric
properties make it impossible to achieve a force locus comparable to that of the ideal case of a 'rotating bar'.
For the other joints these effects are overcome by increasing the mass of the rotating link alas at the expense of increasing the magnitude of the force. The transmission angle has a noticeable effect, a better transmission angle results in a better joint force with respect to rate of change of direction.

Though the results presented are for one starting point for each example, several other starting points were tried and the results were worse than those presented. To continue trying alternative starting points in quest of better results is very much time consuming. It is felt that further investigation is necessary for choosing suitable starting points.
CHAPTER ELEVEN

DISCUSSION, CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK
11.1 TOLERANCE AND CLEARANCE ALLOCATION

11.1.1 Discussion

It has been possible to use the simple statistical relationship $\Delta^2 = \sum P_i^2 \delta_i^2$ (relating the output deviation $\Delta$ to the deviations of the component dimensions $\delta_i$ taking into account the sensitivity coefficients $P_i$) since the critical dimensions involved are not subject to drift in the manufacturing process. These dimensions are the joint centre distances and the machining operation is simply boring of holes. The distributions of the component dimensions will therefore be nearly normal and since the operation is the same for all the dimensions involved, the standard deviations will be nearly equal.

In determining the allowable deviations on the component dimensions the peak values ($P_{i*}$) of the sensitivity coefficients were used rather than the r.m.s. values. This was done because the concern here is the allocation of tolerances and clearances such that the output deviation does not exceed the specified limits at any time during the cycle of motion of the mechanism.

The computer program has been debugged and tested using a representative sample of the linkage mechanisms it is designed to handle, viz. planar multi-link function and path-generator mechanisms obtained by the addition of one or more dyads to a basic unit consisting of a frame and an input link pivoted to it. Though no comparable programs exist against
which the efficiency could be measured, the execution times (see computer print outputs, Chapter VI) for the example problems may indicate such a measure especially in comparison with methods which use iterative optimization techniques.

The results are presented such that they may be directly related to the input data and the sketches from which the input data is compiled. It was intended to give the tolerances and clearances in terms of the ISO standard tolerance grades, however this would require, in the case of clearances, providing the nominal dimensions of the pins and bores at the joints. These dimensions are determined based on the loading on the mechanism. Such an analysis is beyond the scope of the present investigation.

The graphical output gives a very useful picture of the variations of the sensitivity coefficients and the output deviation throughout the cycle of motion of a mechanism and provides clues for possible improvements of the mechanism. It shows which parameters are critical and at which positions along the cycle.

11.1.2 Conclusions

A simple and fast method for allocating tolerances and clearances in a wide range of plane linkage mechanisms has been developed. The method has been incorporated into a computer program which will fill a gap in the computer aided design of linkage mechanisms. The program uses input data structured in the same way as that for the linkage mechanism
synthesis and analysis programs at the Design Unit, University of Newcastle with a minimum of additional parameters, viz. cost-tolerance relationship constants and output tolerance specifications.

The results obtained using this program compare satisfactorily with those of other methods (see Chapter VI). These methods treated four-bar linkages only, whereas the present method is more general in that it is directly applicable to multi-link mechanisms.

11.1.3 Suggestions for Further Work

The method presented here caters for plane mechanisms with revolute joints. An area of further work is extending the method to cater for mechanisms with sliding joints where the effect of relative rotation of the sliding pair elements due to presence of clearance (see Chapter III) is accounted for.

Another area of further work, though not directly related to the present investigation, is the developing of a method for determining the shapes and dimensions (other than arc lengths) of the links of a mechanism based on the loading and other functional requirements. Availability of information produced by such a method would allow the present method to give the results in terms of standard tolerance grades.
11.2 MAINTAINING CONTACT IN JOINTS

11.2.1 Discussion

The analysis presented is simple and straightforward. The boundary limits imposed on the optimization variables plus the limitations due to arc lengths proportions which dictate the kinematic (or geometric) properties of the linkage may be among the reasons which prevent the optimization run from converging to a near ideal result, i.e. joint forces similar to that for a bar rotating about a pin (Chapter VIII) at constant angular velocity. Nevertheless the results for the examples (Chapter X) show a definite tendency to approach the ideal situation, especially for the frame/crank and crank/coupler joints. The fact that the results for the linkage with the better transmission angle and for the drag link approach the ideal more closely than does that for the linkage with the poor transmission angle supports the argument that the kinematic properties of the linkage have a great influence on the results.

The objective function used may have been too restrictive since the ideal conditions set (i.e. constant force and constant rate of rotation) are impossible to achieve. This is most severe for the case of a crank rocker where the joint forces for the coupler/follower and follower/frame joints have, by virtue of the geometric properties, restricted changes in direction. The objective function used here is therefore not suitable and need to be changed to take this into account. An
alternative may be used as objective function such as

\[ f = \sum_{i=1}^{m} \sum_{j=1}^{n} F_{ij}^2 \]

where \( F_{ij} \) is the magnitude of the joint force, for joint 'i' at an input crank position 'j'.

- \( m \) is the number of joints in the mechanism
- \( n \) is the number of input positions,

and minimizing the function subject to inequality constraints

\[ \frac{\dot{y}_{ij}}{F_{ij}} < 1 \]

where \( \dot{y}_{ij} \) is the rate of change of direction of \( F_{ij} \).

Since, for a given linkage, the kinematic properties may not be altered at this stage of linkage design, either of two courses of action may be taken if the result is not satisfactory. The first is to find a different linkage, e.g. a cognate linkage, which may have more favourable kinematic properties. The second is to achieve the conditions for maintaining contact by an alternative method such as the force-form closure described by Fawcett [49].
Another factor which decides the success of the optimization is the choice of the starting point (i.e. setting the initial or starting values of the optimization variables). This is crucial because it is most likely that the optimization converges to the local minimum nearest to the starting point. This means that several starting points must be tried which can be cumbersome when the number of variables is large. The choice of the starting point seems to be even more critical in the case of the angular optimization variables where the objective function is a function of the sines or cosines of these variables. Due to this the objective function will be sinusoidal and hence more prone to be trapped into a local minimum as regards the angular variables.

11.2.2 Conclusions

The results have shown that mass re-distribution may be used to approach conditions for maintaining contact in the joints of a four bar mechanism. How far these conditions are approached depends on the kinematic properties of the linkage and on the choice of the starting point.

11.2.3 Suggestions for Further Work

Further work is required to refine the method and to develop a method for choosing a suitable starting point. The objective function formulation may need to be revised. In the present method it was formulated around the ideal situation of a constant joint force \( R \) rotating at a constant rate \( \dot{\gamma} \) which is impossible to achieve at the joints not
associated with links rotating at constant angular velocities. This may still need to be used as a reference, but restructuring the function and/or using an alternative optimization algorithm need further investigation.

Eventually the investigation needs to be extended to cover multi-link mechanisms.
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REFERENCES

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TABLES
**TABLE 6.1**

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************
**/ Tocalm | OSMAN | FEB 82 /**
**/ FOUR-BAR SINE FUNCTION GENERATOR

**LINEAR DIMENSIONS ARE IN INCHES**

**OUTPUT TOLERANCE = 1,000 DEGREES**

**TOLERANCES ON ARC LENGTHS :-**

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<thead>
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<th>ARC NUMBER</th>
<th>LOOP NUMBER</th>
<th>ARC LENGTH</th>
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<tr>
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<td>2.070</td>
<td>0.3570E-02</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2.421</td>
<td>0.4364E-02</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0.746</td>
<td>0.2092E-02</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1.000</td>
<td>0.2497E-02</td>
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**CLEARANCES IN JOINTS :-**

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<th>LOOP NUMBER</th>
<th>CLEARANCE</th>
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<tbody>
<tr>
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<td>1</td>
<td>0.1785E-02</td>
</tr>
<tr>
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<td>1</td>
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<tr>
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<td>0.1246E-02</td>
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</table>

**OUTPUT ARC :-**

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</table>

**INPUT REFERENCE POSITION :-**

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</thead>
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</table>

**EXECUTION TIME**

0.285 CPU SEC.
TABLE 6.2
FOUR-BAR SINE FUNCTION GENERATOR: COMPARISON OF RESULTS

<table>
<thead>
<tr>
<th>NAME AND SYMBOL</th>
<th>NOMINAL DIMENSION</th>
<th>TOLERANCES AND CLEARANCES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>PRESENT WORK</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WITHOUT COST OPTIMIZATION</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input Ref. Angle $\gamma_c$</td>
<td>116.211°</td>
<td>$\epsilon_c = 0.496°$</td>
</tr>
<tr>
<td>Output Arc Angle $\gamma_c$</td>
<td>287.148°</td>
<td>$\epsilon_o = 0.408°$</td>
</tr>
<tr>
<td>Crank, $a_{1,1}$</td>
<td>2.06980&quot;</td>
<td>$\tau_{1,1} = 2.47$</td>
</tr>
<tr>
<td>Coupler, $a_{2,1}$</td>
<td>2.42146&quot;</td>
<td>$\tau_{2,1} = 2.41$</td>
</tr>
<tr>
<td>Follower, $a_{3,1}$</td>
<td>0.74613&quot;</td>
<td>$\tau_{3,1} = 2.94$</td>
</tr>
<tr>
<td>Frame, $a_{4,1}$</td>
<td>1.0000</td>
<td>$\tau_{4,1} = 2.43$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$c_{1,2,1} = 1.205$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$c_{2,3,1} = 1.205$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$c_{3,4,1} = 1.215$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$c_{4,1,1} = 1.215$</td>
</tr>
</tbody>
</table>

Linear Tolerances and Clearances are in $10^{-3}$ in.
**TABLE 6.3**

Linear dimensions are in millimeters

Output tolerance (slider displacement) = 0.250E+00

Tolerances on arc lengths:

<table>
<thead>
<tr>
<th>Arc Number</th>
<th>Loop Number</th>
<th>Arc Length</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>50.000</td>
<td>0.7742E-01</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>200.000</td>
<td>0.1669E+00</td>
</tr>
</tbody>
</table>

Clearances in joints:

<table>
<thead>
<tr>
<th>Preceding Arc Number</th>
<th>Following Arc Number</th>
<th>Loop Number</th>
<th>Clearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0.3871E-01</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>1</td>
<td>0.8345E-01</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>1</td>
<td>0.1000E+00</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>0.3871E-01</td>
</tr>
</tbody>
</table>

Input reference position:

Reference angle = 270.000°
Tolerance on angle = 0.3165E+00°

Execution time
0.326 CPU sec.
**TABLE 6.4**

---

**FOUR-BAR MOTOR-CYCLE REAR SUSPENSION**

**LINEAR DIMENSIONS ARE IN MILLIMETERS**

**OUTPUT TOLERANCE (POLAR CO-ORDINATES)**

RADIAL=0.100E+01  ANGULAR=0.600 DEGREES

**TOLERANCES ON ARC LENGTHS:**

<table>
<thead>
<tr>
<th>ARC NUMBER</th>
<th>LOOP NUMBER</th>
<th>ARC LENGTH</th>
<th>TOLERANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>469.900</td>
<td>0.8905E-01</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>170.200</td>
<td>0.4247E+00</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>429.200</td>
<td>0.1832E+00</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>325.730</td>
<td>0.5299E+00</td>
</tr>
</tbody>
</table>

**CLEARANCES IN JOINTS:**

<table>
<thead>
<tr>
<th>PRECEEDING ARC NUMBER</th>
<th>FOLLOWING ARC NUMBER</th>
<th>LOOP NUMBER</th>
<th>CLEARANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0.4453E-01</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>1</td>
<td>0.4371E-01</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>1</td>
<td>0.9158E-01</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>0.4355E-01</td>
</tr>
</tbody>
</table>

Continued following page....
Table 6.4 (.... continued from preceding page)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>OUTPUT ARC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ARC LENGTH</td>
<td>44.600</td>
<td>0.8741E-01</td>
</tr>
<tr>
<td>ARC ANGLE (DEGREES)</td>
<td>60.000</td>
<td>0.9088E+00</td>
</tr>
<tr>
<td>ORIGIN ARC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ARC LENGTH</td>
<td>148.660</td>
<td>0.8710E-01</td>
</tr>
<tr>
<td>ARC ANGLE (DEGREES)</td>
<td>88.246</td>
<td>0.6880E+00</td>
</tr>
<tr>
<td>INPUT REFERENCE POSITION</td>
<td></td>
<td></td>
</tr>
<tr>
<td>REFERENCE ANGLE (DEGREES)</td>
<td>91.900</td>
<td>0.6951E+00</td>
</tr>
<tr>
<td>EXECUTION TIME</td>
<td>0.470 CPU SEC.</td>
<td></td>
</tr>
<tr>
<td>TOLERANCE ON ANGLE (DEGREES)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ARC NUMBER</td>
<td>LOOP NUMBER</td>
<td>ARC LENGTH</td>
</tr>
<tr>
<td>------------</td>
<td>-------------</td>
<td>------------</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>7.500</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>30.139</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>21.116</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>36.716</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>28.833</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>21.421</td>
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<tr>
<td>4</td>
<td>2</td>
<td>61.832</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>39.998</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ARC NUMBER</th>
<th>LOOP NUMBER</th>
<th>ANGLE MAG. (DEGREES)</th>
<th>TOLERANCE (DEGREES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>179.990</td>
<td>0.3936E+00</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>64.537</td>
<td>0.4175E+00</td>
</tr>
</tbody>
</table>
Table 6.5 (.... continued from preceding page)

CLEARANCES IN JOINTS :-

<table>
<thead>
<tr>
<th>PRECEDING ARC NUMBER</th>
<th>FOLLOWING ARC NUMBER</th>
<th>LOOP NUMBER</th>
<th>CLEARANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0.6028E-02</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>1</td>
<td>0.1451E-01</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>1</td>
<td>0.1451E-01</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>0.6028E-02</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>2</td>
<td>0.1448E-01</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>2</td>
<td>0.1448E-01</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>2</td>
<td>0.2201E-01</td>
</tr>
</tbody>
</table>

OUTPUT ARC :-

ARC ANGLE = 31.090° (DEGREES)  TOLERANCE ON ARC ANGLE = 0.3346E+00 (DEGREES)

INPUT REFERENCE POSITION :-

REFERENCE ANGLE = 212.333° (DEGREES)  TOLERANCE ON ANGLE = 0.1201E+01 (DEGREES)

EXECUTION TIME
1.710 CPU SEC.
**TABLE 6.6**

---

**EIGHT-BAR STRAIGHT LINE GENERATOR**

**LINEAR DIMENSIONS ARE IN MILLIMETERS**

**OUTPUT TOLERANCE (CARTESIAN CO-ORDINATES)**

X-DIRECTION = 0.100E+01  
Y-DIRECTION = 0.500E+01

---

**TOLERANCES ON ARC LENGTHS:**

<table>
<thead>
<tr>
<th>ARC NUMBER</th>
<th>LOOP NUMBER</th>
<th>ARC LENGTH</th>
<th>TOLERANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>177.500</td>
<td>0.1465E+00</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>155.000</td>
<td>0.1177E+00</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>435.000</td>
<td>0.1467E+00</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>177.500</td>
<td>0.1820E+00</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>155.000</td>
<td>0.1177E+00</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>435.000</td>
<td>0.1467E+00</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>155.000</td>
<td>0.1478E+00</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>155.000</td>
<td>0.1652E+00</td>
</tr>
</tbody>
</table>

---

**CLEARANCES IN JOINTS:**

<table>
<thead>
<tr>
<th>PRECEDING ARC NUMBER</th>
<th>FOLLOWING ARC NUMBER</th>
<th>LOOP NUMBER</th>
<th>CLEARANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0.5886E-01</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>1</td>
<td>0.5886E-01</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>1</td>
<td>0.7337E-01</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>0.7323E-01</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>2</td>
<td>0.5886E-01</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>2</td>
<td>0.5886E-01</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>2</td>
<td>0.7335E-01</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>3</td>
<td>0.5886E-01</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>3</td>
<td>0.7389E-01</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>3</td>
<td>0.5886E-01</td>
</tr>
</tbody>
</table>

---

**INPUT REFERENCE POSITION:**

REFERENCE ANGLE = 325.000  (DEGREES)  
TOLERANCE ON ANGLE = 0.1732E+01  (DEGREES)

---

**EXECUTION TIME**

1.524 CPU SEC.
TABLE 6.7

***/ TOCALM | OSMA! | FEB 82 /**
***/ Table 6.7 TEN-BAR NEEDLE MECHANISM

LINEAR DIMENSIONS ARE IN MILLIMETERS

OUTPUT TOLERANCE = 1.000 DEGREES

TOLERANCES ON ARC LENGTHS :-

<table>
<thead>
<tr>
<th>ARC NUMBER</th>
<th>LOOP NUMBER</th>
<th>ARC LENGTH</th>
<th>TOLERANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>19.000</td>
<td>0.5968E-01</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>95.000</td>
<td>0.3101E+00</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>105.500</td>
<td>0.4917E+00</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>112.468</td>
<td>0.1799E+00</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>105.000</td>
<td>0.1714E+00</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>31.000</td>
<td>0.7515E-01</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>110.064</td>
<td>0.2890E+00</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>61.000</td>
<td>0.1173E+00</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>12.500</td>
<td>0.4893E-01</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>24.000</td>
<td>0.8353E-01</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>245.500</td>
<td>0.2431E+00</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>85.000</td>
<td>0.3507E+00</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>352.716</td>
<td>0.3295E+00</td>
</tr>
</tbody>
</table>

TOLERANCES ON ARC ANGLES :-

<table>
<thead>
<tr>
<th>ARC NUMBER</th>
<th>LOOP NUMBER</th>
<th>ANGLE MAG. (DEGREES)</th>
<th>TOLERANCE (DEGREES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2</td>
<td>33.593</td>
<td>0.3463E+00</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>47.384</td>
<td>0.7960E+00</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>20.442</td>
<td>0.1945E+00</td>
</tr>
</tbody>
</table>

Continued following page ....
Table 6.7 (.... continued from preceding page)

CLEARANCES IN JOINTS :-

<table>
<thead>
<tr>
<th>PRECEEDING ARC NUMBER</th>
<th>FOLLOWING ARC NUMBER</th>
<th>LOOP NUMBER</th>
<th>CLEARANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
<td>-0.2984E-01</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>1</td>
<td>-0.1000E+00</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>1</td>
<td>0.4177E-01</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>0.2984E-01</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>2</td>
<td>0.2934E-01</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>2</td>
<td>0.3757E-01</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>2</td>
<td>0.3757E-01</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>3</td>
<td>0.3757E-01</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>3</td>
<td>0.2446E-01</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>3</td>
<td>0.2446E-01</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>4</td>
<td>0.2446E-01</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>4</td>
<td>0.1000E+00</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>4</td>
<td>0.1000E+00</td>
</tr>
</tbody>
</table>

OUTPUT ARC :-

ARC ANGLE = 10.048, TOLERANCE ON ARC ANGLE = 0.6377E+00
(DEGREES) (DEGREES)

INPUT REFERENCE POSITION :-

REFERENCE ANGLE = 121.641, TOLERANCE ON ANGLE = 0.2803E+01
(DEGREES) (DEGREES)

EXECUTION TIME
4.621 CPU SEC.
<table>
<thead>
<tr>
<th>LINK</th>
<th>ARC LENGTH (mm)</th>
<th>ORIGINAL MASS PARAMETERS</th>
<th>ADDITIONAL MASS PARAMETERS (POST-OPTIMIZATION)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$m_0$ (kg)</td>
<td>$\rho_0$ (mm)</td>
</tr>
<tr>
<td>CRANK</td>
<td>50</td>
<td>0.015</td>
<td>25</td>
</tr>
<tr>
<td>COUPLER</td>
<td>100</td>
<td>0.025</td>
<td>50</td>
</tr>
<tr>
<td>FOLLOWER</td>
<td>100</td>
<td>0.025</td>
<td>50</td>
</tr>
<tr>
<td>FRAME</td>
<td>100</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
**TABLE 10.2**

**CRANK-ROCKER WITH ARC LENGTHS 50, 100, 100, 100**

> 31 FUNCTION EVALUATIONS WERE NEEDED BY E04HBF

<table>
<thead>
<tr>
<th>ITNS</th>
<th>FN EVALS</th>
<th>FN VALUE</th>
<th>NORM OF PROJ GRADIENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>2.7801E-01</td>
<td>3.6750E+00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>J</th>
<th>X(J)</th>
<th>G(J)</th>
<th>STATUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5000E-02</td>
<td>1.9299E-01</td>
<td>FREE</td>
</tr>
<tr>
<td>2</td>
<td>3.3000E-02</td>
<td>8.7721E-02</td>
<td>FREE</td>
</tr>
<tr>
<td>3</td>
<td>1.7453E+00</td>
<td>-5.4474E-04</td>
<td>FREE</td>
</tr>
<tr>
<td>4</td>
<td>2.1500E-01</td>
<td>3.2916E-01</td>
<td>FREE</td>
</tr>
<tr>
<td>5</td>
<td>2.1000E-02</td>
<td>3.6065E+00</td>
<td>FREE</td>
</tr>
<tr>
<td>6</td>
<td>1.7453E+00</td>
<td>-1.0730E-02</td>
<td>FREE</td>
</tr>
<tr>
<td>7</td>
<td>1.0000E-02</td>
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**ESTIMATED CONDITION NUMBER OF PROJECTED HESSIAN = 2.50E+05**

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**ESTIMATED CONDITION NUMBER OF PROJECTED HESSIAN = 1.63E+05**
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<td>100</td>
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<td>0.025</td>
<td>0.025</td>
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<tr>
<td>( p_0 ) (mm)</td>
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<td>50</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>( \lambda_0 ) (deg)</td>
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<td>0</td>
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<tr>
<td>( I_{0} ) (kg ( \text{mm}^2 ))</td>
<td>18.5</td>
<td>101.7</td>
<td>101.7</td>
<td>-</td>
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<tr>
<td>( \lambda^* ) (deg)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \rho^* ) (mm)</td>
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<td>5.7</td>
<td>17.8</td>
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<tr>
<td>( I_{*} ) (kg ( \text{mm}^2 ))</td>
<td>238.9</td>
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Table 10.4

Crank-Rocker with arc lengths 50, 100, 100, 132.5

31 function evaluations were needed by E04HBF

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<th>NORM OF PROJ GRADIENT</th>
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Estimated condition number of projected Hessian = 2.78E+05

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Estimated condition number of projected Hessian = 1.93E+05
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<th>ADDITIONAL MASS PARAMETERS (Post-Optimization)</th>
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<td>$\rho_0$ (mm)</td>
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**TABLE 10.6**

**Drag-Link with arc lengths 132.5, 100, 100, 50**

31 function evaluations were needed by E04HBF

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Estimated condition number of projected Hessian is more than 1.0E+6

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Estimated condition number of projected Hessian is more than 1.0E+6
Fig. 3.1  PLAY DUE TO CLEARANCE IN A SLIDING JOINT

(a) SLIDING JOINT  (b) Revolute Joint

Fig. 3.2  JOINTS WITH COMPARABLE PLAY DUE TO CLEARANCE
Fig. 3.3  TEN-BAR PLANAR LINKAGE MECHANISM
Fig. 3.4 CHANGE IN GRADIENT SIGN ACROSS NOMINAL DIMENSION

Fig. 3.5 SIX-BAR PATH GENERATOR LINKAGE
Fig. 4.1 DISTRIBUTION OF ARC-LENGTH ALLOWABLE DEVIATION

Fig. 4.2 DISTRIBUTION OF ARC-ANGLE ALLOWABLE DEVIATION

Fig. 4.3 TRANSFORMATION OF ARC-ANGLE
Fig. 5.1 FLOW CHART OF PROGRAM TOCALM
Fig. 5.2  FLOW CHART OF PROGRAM PSODPLOTS
Fig. 6.1  FOUR-BAR SINE FUNCTION GENERATOR

![Diagram of a four-bar sine function generator]

FOUR-BAR SINE FUNCTION GENERATOR

<table>
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<td>□ a₃, 1</td>
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Fig. 6.2a
FOUR-BAR SINE FUNCTION GENERATOR

Fig. 6.2b

Fig. 6.3
Fig. 6.4 SLIDER-CRANK MECHANISM

[Diagram of a slider-crank mechanism with labels and dimensions]

SLIDER CRANK MECHANISM

[Graph showing output sensitivity to parameter deviation vs. input position (degrees)]

key -

△ \text{a}_{1,1}

▼ \text{a}_{2,1}

□ \text{a}_{4,1}

Fig. 6.5a
SLIDER CRANK MECHANISM

Fig. 6.5b

SLIDER CRANK MECHANISM

max. allowable output deviation

Fig. 6.6
Fig. 6.7 FOUR-MOTOR CYCLE REAR SUSPENSION

FOUR-BAR MOTOR-CYCLE REAR SUSPENSION
sensitivity in polar radius

Fig. 6.8a(i)
FOUR-BAR MOTOR-CYCLE REAR SUSPENSION
sensitivity in polar angle

Fig. 6.8a(ii)

FOUR-BAR MOTOR-CYCLE REAR SUSPENSION
sensitivity in polar radius

Fig. 6.8b(i)
FOUR-BAR MOTOR-CYCLE REAR SUSPENSION
sensitivity in polar angle

![Graph showing sensitivity in polar angle](image)

**Fig. 6.8b(ii)**

FOUR-BAR MOTOR-CYCLE REAR SUSPENSION
sensitivity in polar radius

![Graph showing sensitivity in polar radius](image)

**Fig. 6.8c(i)**
FOUR-BAR MOTOR-CYCLE REAR SUSPENSION
sensitivity in polar angle

\[
\begin{align*}
\text{output sensitivity} & \quad \text{to parameter deviation} \\
\text{(rad)} & \quad \text{(rad)}
\end{align*}
\]

Input position (degrees)

**Fig. 6.8c(ii)**

FOUR-BAR MOTOR-CYCLE REAR SUSPENSION
output deviation in radial direction

Max. allowable output deviation

**Fig. 6.9(i)**
FOUR-BAR MOTOR-CYCLE REAR SUSPENSION
output deviation in polar angle

max. allowable output deviation

Fig. 6.9(ii)
Fig. 6.10 SIX-BAR SINE FUNCTION GENERATOR

SIX-BAR SINE FUNCTION GENERATOR

![Diagram of a six-bar sine function generator](image)

**Key:***

- △ a₁,
- ▲ a₂,
- ○ a₃,
- ● a₄,
SIX-BAR SINE FUNCTION GENERATOR

Fig. 6.11b

key:

- △ a₁, 2
- ▽ a₂, 2
- □ a₃, 2
- ○ a₄, 2
- ◯ a₅, 2

SIX-BAR SINE FUNCTION GENERATOR

Fig. 6.11c
SIX-BAR SINE FUNCTION GENERATOR

Fig. 6.11d

SIX-BAR SINE FUNCTION GENERATOR

Fig. 6.12
Fig. 6.13 EIGHT-BAR STRAIGHT LINE GENERATOR
EIGHT-BAR STRAIGHT LINE GENERATOR
sensitivity in x-direction

output sensitivity to parameter deviation

input position (degrees)

Fig. 6.14a(i)

EIGHT-BAR STRAIGHT LINE GENERATOR
sensitivity in y-direction

output sensitivity to parameter deviation

input position (degrees)

Fig. 6.14a(ii)
EIGHT-BAR STRAIGHT LINE GENERATOR
sensitivity in x-direction

Fig. 6.14b(i)

EIGHT-BAR STRAIGHT LINE GENERATOR
sensitivity in y-direction

Fig. 6.14b(ii)
EIGHT-BAR STRAIGHT LINE GENERATOR
sensitivity in x-direction

Fig. 6.14c(i)

EIGHT-BAR STRAIGHT LINE GENERATOR
sensitivity in y-direction

Fig. 6.14c(ii)
EIGHT-BAR STRAIGHT LINE GENERATOR

sensitivity in x-direction

output sensitivity to parameter deviation (mm/ rad)

input position (degrees)

Fig. 6.14d(i)

EIGHT-BAR STRAIGHT LINE GENERATOR

sensitivity in y-direction

output sensitivity to parameter deviation (mm/ rad)

input position (degrees)

Fig. 6.14d(ii)
EIGHT-BAR STRAIGHT LINE GENERATOR
output deviation in x-direction

Fig. 6.15(i)

EIGHT-BAR STRAIGHT LINE GENERATOR
output deviation in y-direction

Fig. 6.15(ii)
TEN-BAR NEEDLE MECHANISM

**Fig. 6.16a**

![Graph showing output sensitivity deviation vs. input position in degrees for ten-bar needle mechanism.](image)

- **Key:**
  - ▲ a 1, 1
  - ▼ a 2, 1
  - □ a 3, 1
  - ◇ a 4, 1

TEN-BAR NEEDLE MECHANISM

**Fig. 6.16b**

![Graph showing output sensitivity deviation vs. input position in degrees for ten-bar needle mechanism.](image)

- **Key:**
  - ▲ a 1, 2
  - ▼ a 2, 2
  - □ a 3, 2
  - ◇ a 4, 2
TEN-BAR NEEDLE MECHANISM

Fig. 6.16c

TEN-BAR NEEDLE MECHANISM

Fig. 6.16d
Figure 6.16e: Output sensitivity of the ten-bar needle mechanism to parameter deviation as a function of input position in degrees.

Key 1:
- $Y_{4,2}$

Figure 6.16f: Output sensitivity of the ten-bar needle mechanism to parameter deviation as a function of input position in degrees.

Key 1:
- $Y_{5,3}$
TEN-BAR NEEDLE MECHANISM

![Graph](image)

**Fig. 6.16g**

TEN-BAR NEEDLE MECHANISM

![Graph](image)

**Fig. 6.16h**
TEN-BAR NEEDLE MECHANISM

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Fig. 6.17

---

max. allowable output deviation
Fig. 8.1 BAR ROTATING IN A HORIZONTAL PLANE

\[ F = m \omega^2 r \]

Fig. 8.2 COMPONENT VECTORS OF JOINT FORCES
Fig. 8.3  MASS DISTRIBUTION PARAMETERS

Fig. 8.4  FOUR-BAR LINKAGE SHOWING ARCS AND MASS CENTRES
Fig. 8.5  FREE-BODY DIAGRAMS OF FOUR-BAR LINKAGE MEMBERS
MAIN PROGRAM

Start

Read input data

not satisf.

Check scale of funct.
satisf.

Print error msg. 'Rescale problem'

not satisf.

Check scale of funct.
satisf.

Print error msg. 'Rescale problem'

not satisf.

Check scale of funct.
satisf.

Print error msg. 'Rescale problem'

SUBROUTINES

MONIT
monitor progress of optimization

FUNCTION
Compute kinematics, mass distribution, joint forces, and objective function

RESULT
Print out res.: final optimiz. variables, mass distribution & joint forces

LIBRARY ROUTINES

*NAG

E04HBF
compute steplength for numeric.
different.

E04JBF
minimize function

Et c.

Fig. 9.1 FLOW CHART OF PROGRAM CONTACT
MAIN PROGRAM

Start

Read input data

Set up parameters of plot

Stop

SUBROUTINES

SKALE
Determine scales of plot

LIBRARY ROUTINE

*GHOST
Routines for
drawing
lines,
curves,
characters,
symbols,
etc.

Fig. 9.2 FLOW CHART OF PROGRAM PINFORCE
CRANK-ROCKER WITH ARC LENGTHS 50, 100, 100, 100

Fig. 10.1 JOINT FORCE PLOTS PRE-OPTIMIZATION FOR CRANK-ROCKER WITH POOR TRANSMISSION ANGLE
CRANK-ROCKER WITH ARC LENGTHS 50, 100, 100, 100

force exerted by frame on crank

force exerted by crank on coupler

force exerted by coupler on follower

force exerted by frame on follower

Fig. 10.2  JOINT FORCE PLOTS POST-OPTIMIZATION FOR CRANK-ROCKER WITH POOR TRANSMISSION ANGLE
CRANK-ROCKER WITH ARC LENGTHS 50, 100, 150, 132.5

force exerted by frame on crank

force exerted by crank on coupler

force exerted by coupler on follower

force exerted by frame on follower

Fig. 10.3 JOINT FORCE PLOTS PRE-OPTIMIZATION FOR CRANK-ROCKER WITH IMPROVED TRANSMISSION ANGLE
CRANK-ROCKER WITH ARC LENGTHS 50, 100, 100, 132.5

Fig. 10.4  JOINT FORCE PLOTS POST-OPTIMIZATION FOR CRANK-ROCKER WITH IMPROVED TRANSMISSION ANGLE
DRAG-LINK WITH ARC LENGTHS $132.5$, $100$, $100$, $50$

![Joint Force Plots Pre-Optimization for Drag-Link](image)

*Fig. 10.5* JOINT FORCE PLOTS PRE-OPTIMIZATION FOR DRAG-LINK
DRAG-LINK WITH ARC LENGTHS 132.5, 100, 100, 50

Fig. 10.6 JOINT FORCE PLOTS POST-OPTIMIZATION FOR DRAG-LINK
APPENDIX I A

LISTING OF COMPUTER PROGRAM

TOCALM
DIMENSION ILHD(10), IGHD(10), DESX(37), DESY(37), DESANG(37),
1 ANMULT(37), XMULT(37), YMULT(37), OPLow(30), OPHIGH(30),
2 IVA(100), IVG(100), MRNRU(100), MGHRU(100), XO(37),
3 YO(37), RO(37), TO(37), AO(37), SO(37), XM(37), YM(37),
4 RH(37), TM(37), AM(37), SM(37), LORDER(105), PDAP(100),
5 PGAP(100), COSTA(105), COSTG(105), TOLER(105),
6 TOLEG(105), TOLED(105), DIFA(105), DIFG(105), IREP(100),
7 ITERN(100)

COMMON ARCL(100), AARCL(100), GAMAN(100), GGAMA(100), DEGINC,
1 IKDN(361), ILINK(100), ILOOP(100), IITLE(18), Iplot, KKL,
2 KKH, KKN, KKO, MAXARC, NLOOP, NFORM, NPOINT, MOTORT, IANG,
3 MOTION, NDES, KON, ILINK(100), ILOOP(100), KLINK(100)

COMMON /CORR/ /OUTOLX, /OUTOLY, /OUTOLA, /OUTOLR, /OUTOLT, /OUTOLS,
1 PD(37,100), PDY(37,100), PDGX(37,100), PDGY(37,100),
2 PDA(37,100), PGDA(37,100), PDR(37,100), PDT(37,100),
3 PDGR(37,100), PDGT(37,100), PDS(37,100), PDGS(37,100),
4 PDOLX(37), PDOLY(37), PDOLGX(37), PDOLGY(37), PDOLRX(37),
5 PDOLRY(37), PDORGX(37), PDORGY(37), PDORX(37), PDORY(37),
6 PDOLR(37), PDOLT(37), PDGR(37), PDGT(37), PDOLR(37),
7 PDOLRT(37), PDGRRT(37), PDGRRT(37), PDCR(37),
8 PDGRA(37), PDRCRA(37), PDCR(37), TL(105), TGL(105),
9 DEVX(37), DEVY(37), DEVA(37), DEVT(37), DEVS(37),
10 FACTOR, MOTN

COMMON /XYZNUR/ /XGR(37), YGR(37), SGR(37), AGR(37), RGR(37),
1 TGR(37)

COMMON /REST/ /CONFIG(10), /DELT(361), /SLIDE(10), CRNKI, HPI, PI,
1 DEGRAD, RINC, THOSTA, IJOINl(10), LARCl(100), LARCF(100),
2 LARCl(20), LOP(10), KKL, KOLL(5), KTHETA, LBA, LKFIN,
3 LKOUT, LKR, LKRET, MOVER, NFROUT, NCOL, NLIN, NOTULK,
4 NOTULP, IDEL, IDELV, IDELA, IVEL, IACC, LCOl(5), TANGLE

EQUIVALENCE (DESX(I), DESY(I), DESANG(I), ANMULT(I), XMULT(I), YMULT(I)
1 OPLow(I), OPHIGH(I), IKA(K), IVG(I), IVG(I),
2 (XO(I), AO(I), RO(I), SO(I)), (YO(I), TO(I))

CALL FTNCMD('SEMPTY FU7; ')
Listing of TOCALM at 16:46:02 on JUL 23, 1982 for CCid=MCB8

CALL FTNCMD('ASSIGN 7=FU7(*L+1);')

CALL TIME(0)

59  !
60 10 CALL TIME(0)
61.
62  PI = 4.0 * DATAN(1.0D0)
63  HPI = PI / 2.0
64  DEGRAD = PI / 180.0
65  TANGLE = 50.0
66  CRNKI = 0
67  CRNKD = 0
68  CRNK2D = 0
69  OFFSET = 0
70  ORIGNG = 0
71  ORIGLK = 0
72  OUTANG = 0
73  OUTLK = 0
74  IPILOT = 0
75  IANG = 9999
76  IDEL = 0
77  KT = 1
78  NDES = 0
79  NPOINT = 0
80  MOTION = 9999
81  IANG = 9999
82  FACTOR = 1.0D+0
83  IUNITS = 1
84  DO 20 IC = 1, 105
85  COSTA(IC) = 1.0D+0
86  COSTB(IC) = 1.0D+0
87 20 CONTINUE

88 C
89 READ (5,1050) ITITLE
90 READ (5,LINKS)
91 READ (5,METHOD)
92 READ (5,LIMITS)
93 C
94 IF (NDES .EQ. 0) NDES = NPOINT
95 IF (MOTION .GT. 3) MOTION = IANG
96 C
97 KKL = NLOOP * MAXARC
98 KKM = KKL + 1
99 KKN = KKM + 1
100 KKO = NLOOP + 1
101 DO 30 I = 1, KKL
102 IILOOP(I) = ILOOPM
103 IILINK(I) = ILINKM
104 KLINK(I) = ILINK(I)
105 30 CONTINUE

106 ALPHA = 2.5D-1 * DEGRAD
107 IF (IUNITS .EQ. 1) CLIMIT = 1.0D-1
108 IF (IUNITS .EQ. 2) CLIMIT = 4.0D-3
109 DO 40 J = 1, KKO
110 TLA(J) = 1.0D+3
111 TLG(J) = 1.0D+3
112 TOLER(J) = CLIMIT
113 TOLEG(J) = 2.5D-1
114 TOLED(J) = ALPHA
115 DIFA(J) = 0.0D+0
116 DIFG(J) = 0.0D+0
117  40 CONTINUE
118  KTHETA = KTHETA + 1
119  ARCL(KKM) = OUTLK
120  ARCL(KKN) = ORIGLK
121  ARCL(KKO + 1) = OFFSET
122  GAMA(KKM) = OUTANG
123  GAMA(KKN) = ORIGNG
124  GAMA(KKO) = CRNKI
125  DO 50 I = 1, KKN
126     AARCL(I) = ARCL(I)
127     GGAMAH) = GAMA(I)
128  50 CONTINUE
129  WRITE (6,1060) ITITLE
130  IF (IUNITS .EQ. 1) WRITE (6,1070)
131  IF (IUNITS .EQ. 2) WRITE (6,1080)
132  C
133  MOTN = MOTION + 1
134  C
135  WRITE (7) ITITLE
136  WRITE (7) MOTN, NDES, IUNITS, MAXARC, NLOOP, KKL
137  WRITE (7) (DELT(I),I=1,NDES)
138  C
139  NCK = 0
140  CALL KALM
141  GO TO (60, 80, 100, 120), MOTN
142  C
143  60 DO 70 IP = 1, NDES
144     XM(IP) = XGR(IP)
145     YM(IP) = YGR(IP)
146  70 CONTINUE
147  XYRAT = OUTOLX / OUTOLY
148  WRITE (6,1090) OUTOLX, OUTOLY
149  GO TO 140
150  C
151  80 DO 90 IP = 1, NDES
152     AM(IP) = AGR(IP)
153  90 CONTINUE
154  WRITE (6,1100) OUTOLA
155  GO TO 140
156  C
157  100 DO 110 IP = 1, NDES
158     RM(IP) = RGR(IP)
159     TN(IP) = TGR(IP)
160  110 CONTINUE
161  RTRAT = OUTOLR / (OUTOLT*DEGRAD)
162  WRITE (6,1110) OUTOLR, OUTOLT
163  GO TO 140
164  C
165  120 DO 130 IP = 1, NDES
166     SM(IP) = SGR(IP)
167  130 CONTINUE
168  WRITE (6,1120) OUTOLS
169  C
170  140 CALL RESET(1)
171  NCK = NCK + 1
172  NNR = 0
173  IRR = 0
174  IGNR = 0
Listing of TOCALM at 16:46:02 on JUL 23, 1982 for CCid=MCB8

175  C
176  150  NNUR = NNUR + 1
177  IREP(NNUR) = 0
178  ITERN(NNUR) = 0
179  IF (NNUR .GT. KKL) GO TO 550
180  LPNUR = (NNUR - 1) / MAXARC + 1
181  IF (ILINK(NNUR)) 160, 150, 170
182  160  IF (ILOOP(NNUR)) 150, 210, 180
183  170  IF (ILOOP(NNUR)) 150, 210, 190
184  180  JL = (ILOOP(NNUR) - 1) * MAXARC - ILINK(NNUR)
185  IF (ILOOP(JL) .LT. 0) GO TO 210
186  IF (GAMA(NNUR) .EQ. I. BD02 AND. ARCUNNUR .EQ. ARCLUM) 160 TO 200
187  IF (ITERN(JL) .EQ. 0) ITERN(JL) = JL
188  ITERN(NNUR) = ITERN(JL)
189  GO TO 340
190  190  IF (ILOOP(NNUR) .EQ. LPNUR) GO TO 210
191  ILOOP(NNUR) = -ILINK(NNUR)
192  ILINK(NNUR) = ILINK(NNUR)
193  C
194  JL = (ILOOP(NNUR) - 1) * MAXARC - ILINK(NNUR)
195  200  IF (IREP(JL) .EQ. 0) IREP(JL) = JL
196  IREP(NNUR) = IREP(JL)
197  IF (ILOOP(IREP(NNUR)) .LT. 0) GO TO 150
198  C
199  210  IRNUR = IRNUR + 1
200  MNRUR(IRNUR) = NNUR
201  C
202  210  IRNUR = IRNUR + 1
203  C
204  IF (ARCL(NNUR) .GE. TOLER(NNUR)) ARCL(NNUR) = ARCL(NNUR) - TOLER(NNUR)
205  C
206  TDF = 1.0D+0
207  IF (ARCL(NNUR) .LT. TOLER(NNUR)) TDF = 5.0D-1
208  CALL KALM
209  C
210  GO TO (220, 250, 280, 310), NDTM
211  C
212  220  DO 230 IP = 1, NDES
213  X0(IP) = XGR(IP)
214  Y0(IP) = YGR(IP)
215  230  CONTINUE
216  CALL RESET(2)
217  ARCL(NNUR) = ARCL(NNUR) + TOLER(NNUR)
218  CALL KALM
219  PDAP(NNUR) = 0.0D+0
220  DO 240 IP = 1, NDES
221  PDX(IP,NNUR) = (DABS(XGR(IP) - X0(IP)) + DABS(XM(IP) - X0(IP))) / ((2.0+TOLER(NNUR))TDF)
222  IF (PDX(IP,NNUR) .GT. PDAP(NNUR)) PDAP(NNUR) = PDX(IP,NNUR)
223  PDY(IP,NNUR) = (DABS(YGR(IP) - YM(IP)) + DABS(YM(IP) - Y0(IP))) / ((2.0+TOLER(NNUR))TDF)
224  IF (XYRAT*PDY(IP,NNUR) .GT. PDAP(NNUR)) PDAP(NNUR) = XYRAT * PDY(IP,NNUR)
225  C
226  240  CONTINUE
227  CALL RESET(2)
228  GO TO 150
229  C
230  250  DO 260 IP = 1, NDES
Listing of TOCALM at 16:46:02 on JUL 23, 1982 for CCid=MCB8

233 A0(IP) = AGR(IP)
234 260 CONTINUE
235 CALL RESET(2)
236 ARCL(NNUR) = ARCL(NNUR) + TOLER(NNUR)
237 CALL KLM
238 PDAP(NNUR) = 0.0D+0
239 DO 270 IP = 1, NDES
240 PDA(IP,NNUR) = (DABS(AGR(IP) - AM(IP)) + DABS(AM(IP) - A0(IP))
241 1 / (2.0*TOLER(NNUR)*TDF)
242 IF (PDA(IP,NNUR) GT. PDAP(NNUR)) PDAP(NNUR) = PDA(IP,NNUR)
243 270 CONTINUE
244 CALL RESET(2)
245 GO TO 150
246 C
247 280 DO 290 IP = 1, NDES
248 RO(IP) = RGR(IP)
249 TO(IP) = TGR(IP)
250 290 CONTINUE
251 CALL RESET(2)
252 ARCL(NNUR) = ARCL(NNUR) + TOLER(NNUR)
253 CALL KLM
254 PDAP(NNUR) = 0.0D+0
255 DO 300 IP = 1, NDES
256 PDR(IP,NNUR) = (DABS(RGR(IP) - RM(IP)) + DABS(RM(IP) - RO(IP))
257 1 / (2.0*TOLER(NNUR)*TDF)
258 IF (PDR(IP,NNUR) GT. PDAP(NNUR)) PDAP(NNUR) = PDR(IP,NNUR)
259 PDT(IP,NNUR) = (DABS(TGR(IP) - TM(IP)) + DABS(TM(IP) - TO(IP))
260 1 / (2.0*TOLER(NNUR)*TDF)
261 IF (RTRAT*PDT(IP,NNUR) GT. PDAP(NNUR)) PDAP(NNUR) = RTRAT *
262 1 PDT(IP,NNUR)
263 300 CONTINUE
264 CALL RESET(2)
265 GO TO 150
266 C
267 310 DO 320 IP = 1, NDES
268 S0(IP) = SGR(IP)
269 320 CONTINUE
270 CALL RESET(2)
271 ARCL(NNUR) = ARCL(NNUR) + TOLER(NNUR)
272 CALL KLM
273 PDAP(NNUR) = 0.0D+0
274 DO 330 IP = 1, NDES
275 PSD(IP,NNUR) = (DABS(SGR(IP) - SM(IP)) + DABS(SM(IP) - S0(IP))
276 1 / (2.0*TOLER(NNUR)*TDF)
277 IF (PSD(IP,NNUR) GT. PDAP(NNUR)) PDAP(NNUR) = PSD(IP,NNUR)
278 330 CONTINUE
279 CALL RESET(2)
280 GO TO 150
281 C
282 C
283 340 IRNUR = IRNUR + 1
284 IGNUR = IGNUR + 1
285 MRNUR(IRNUR) = NNUR
286 MGMR(IGNUR) = NNUR
287 C
288 IF (ARCL(NNUR) GE. TOLER(NNUR)) ARCL(NNUR) = ARCL(NNUR) - TOLER(1
289 NNUR)
290 TDF = 1.0D+0
IF (ARCL(NNUR) .LT. TOLER(NNUR)) TDF = 5.0D-1

CALL KALM

GO TO (350, 400, 450, 500), MOTH

350 DO 360 IP = 1, NDES
XO(IP) = XGR(IP)
YO(IP) = YGR(IP)
360 CONTINUE

CALL RESET(2)
ARCL(NNUR) = ARCL(NNUR) + TOLER(NNUR)

DO 370 IP = 1, NDES
PDX(IP,NNUR) = (DABS(XGR(IP) - XM(IP)) + DABS(XM(IP) - XO(IP)))
1 / (2.0*TOLER(NNUR)*TDF)
IF (PDX(IP,NNUR) .GT. PDAP(NNUR)) PDAP(NNUR) = PDX(IP,NNUR)
PDY(IP,NNUR) = (DABS(YGR(IP) - YM(IP)) + DABS(YM(IP) - YO(IP)))
1 / (2.0*TOLER(NNUR)*TDF)
IF (XYRAT*PDY(IP,NNUR) .GT. PDAP(NNUR)) PDAP(NNUR) = XYRAT *
1
370 CONTINUE

CALL RESET(2)

GANA(NNUR) = GAMA(NNUR) - TOLEG(NNUR)

CALL KALM
DO 380 IP = 1, NDES
XO(IP) = XGR(IP)
YO(IP) = YGR(IP)
380 CONTINUE

CALL RESET(2)
GANA(NNUR) = GAMA(NNUR) + 7OLEG(NNUR)

CALL KALM
PGAP(NNUR) = 0.0D+0

DO 390 IP = 1, NDES
PDGX(IP,NNUR) = (DABS(AGR(IP) - AM(IP)) + DABS(AM(IP) - AO(IP)))
1 / (2.0D+0*TOLED(NNUR))
IF (PDGX(IP,NNUR) .GT. PDAP(NNUR)) PDAP(NNUR) = PDGX(IP,NNUR)
PDGY(IP,NNUR) = (DABS(YGR(IP) - YM(IP)) + DABS(YM(IP) - YO(IP)))
1 / (2.0D+0*TOLED(NNUR))
IF (XYRAT*PDGY(IP,NNUR) .GT. PDAP(NNUR)) PDAP(NNUR) = XYRAT *
1
390 CONTINUE

CALL RESET(2)

GO TO 150

400 DO 410 IP = 1, NDES
AO(IP) = AGR(IP)
410 CONTINUE

CALL RESET(2)
ARCL(NNUR) = ARCL(NNUR) + TOLER(NNUR)

CALL KALM
PDAP(NNUR) = 0.0D+0

DO 420 IP = 1, NDES
PDA(IP,NNUR) = (DABS(AGR(IP) - AM(IP)) + DABS(AM(IP) - AO(IP)))
1 / (2.0*TOLER(NNUR)*TDF)
IF (PDA(IP,NNUR) .GT. PDAP(NNUR)) PDAP(NNUR) = PDA(IP,NNUR)
420 CONTINUE
Listing of TOCALM at 16:46:02 on JUL 23, 1982 for CCid=MCBB

```fortran
CALL RESET(2)
C
GAMA(NNUR) = GAMA(NNUR) - TOLEG(NNUR)
CALL KALM
DO 430 IP = 1, NDES
   A0(IP) = AGR(IP)
430 CONTINUE
CALL RESET(2)
GAMA(NNUR) = GAMA(NNUR) + TOLEG(NNUR)
CALL KALM
PGAP(NNUR) = 0.0D+0
DO 440 IP = 1, NDES
   PDGA(IP,NNUR) = (DABS(AGR(IP) - AM(IP)) + DABS(AM(IP) - A0(IP)))
   1 / (2.0D+0*TOLEG(NNUR))
   IF (PDGA(IP,NNUR) .GT. PGAP(NNUR)) PGAP(NNUR) = PDGA(IP,NNUR)
440 CONTINUE
CALL RESET(2)
GO TO 150
C
450 DO 460 IP = 1, NDES
   RO(IP) = RGR(IP)
   TO(IP) = TGR(IP)
460 CONTINUE
CALL RESET(2)
ARCL(NNUR) = ARCL(NNUR) + TOLER(NNUR)
CALL KALM
PDAP(NNUR) = 0.0D+0
DO 470 IP = 1, NDES
   PDR(IP,NNUR) = (DABS(RGR(IP) - RM(IP)) + DABS(RM(IP) - RO(IP)))
   1 / (2.0*TOLEG(NNUR)*TDF)
   IF (PDR(IP,NNUR) .GT. PDAP(NNUR)) PDAP(NNUR) = PDR(IP,NNUR)
   PDT(IP,NNUR) = (DABS(TGR(IP) - TM(IP)) + DABS(TM(IP) - TO(IP)))
   1 / (2.0*TOLEG(NNUR)*TDF)
   IF (RTRAT*PDT(IP,NNUR) .GT. PDAP(NNUR)) PDAP(NNUR) = RTRAT *
   1 PDT(IP,NNUR)
470 CONTINUE
CALL RESET(2)
C
GAMA(NNUR) = GAMA(NNUR) - TOLEG(NNUR)
CALL KALM
DO 480 IP = 1, NDES
   RO(IP) = RGR(IP)
   TO(IP) = TGR(IP)
480 CONTINUE
CALL RESET(2)
GAMA(NNUR) = GAMA(NNUR) + TOLEG(NNUR)
CALL KALM
PGAP(NNUR) = 0.0D+0
DO 490 IP = 1, NDES
   PDGR(IP,NNUR) = (DABS(RGR(IP) - RM(IP)) + DABS(RM(IP) - RO(IP)))
   1 / (2.0D+0*TOLEG(NNUR))
   IF (PDGR(IP,NNUR) .GT. PGAP(NNUR)) PGAP(NNUR) = PDGR(IP,NNUR)
   PDGT(IP,NNUR) = (DABS(TGR(IP) - TM(IP)) + DABS(TM(IP) - TO(IP)))
   1 / (2.0D+0*TOLEG(NNUR))
   IF (RTRAT*PDGT(IP,NNUR) .GT. PGAP(NNUR)) PGAP(NNUR) = RTRAT *
   1 PDGT(IP,NNUR)
490 CONTINUE
CALL RESET(2)
```

Listing of TOCALM at 16:46:02 on JUL 23, 1982 for CCid=MCBB

407    GO TO 150
408    C
409    500 DO 510 IP = 1, NDES
410    SO(IP) = SGR(IP)
411    510 CONTINUE
412    CALL RESET(2)
413    ARCL(NNUR) = ARCL(NNUR) + TOLER(NNUR)
414    CALL KALM
415    PDAP(NNUR) = 0.0D+0
416    DO 520 IP = 1, NDES
417    PDS(IP,NNUR) = (DABS(SGR(IP) - SM(IP)) + DABS(SM(IP) - SO(IP)))
418    1 / (2.0D+TOLER(NNUR)*TDF)
419    IF (PDS(IP,NNUR) .GT. PDAP(NNUR)) PDAP(NNUR) = PDS(IP,NNUR)
420    520 CONTINUE
421    CALL RESET(2)
422    C
423    GAMA(NNUR) = GAMA(NNUR) - TOLEG(NNUR)
424    CALL KALM
425    DO 530 IP = 1, NDES
426    SO(IP) = SGR(IP)
427    530 CONTINUE
428    CALL RESET(2)
429    GAMA(NNUR) = GAMA(NNUR) + TOLEG(NNUR)
430    CALL KALM
431    PGAP(NNUR) = 0.0D+0
432    DO 540 IP = 1, NDES
433    PDGS(IP,NNUR) = (DABS(SGR(IP) - SM(IP)) + DABS(SM(IP) - SO(IP)))
434    1 / (2.0D+TOLER(NNUR))
435    IF (PDGS(IP,NNUR) .GT. PGAP(NNUR)) PGAP(NNUR) = PDGS(IP,NNUR)
436    540 CONTINUE
437    CALL RESET(2)
438    GO TO 150
439    C
440    C
441    550 GO TO (560, 570, 720, 830), HOTN
442    C
443    560 IF (ARCL(KKM) .LT. 0.1D-3) GO TO 605
444    ARCL(KKM) = ARCL(KKM) - TOLER(KKM)
445    CALL KALM
446    DO 570 IP = 1, NDES
447    X0(IP) = XGR(IP)
448    Y0(IP) = YGR(IP)
449    570 CONTINUE
450    CALL RESET(2)
451    ARCL(KKM) = ARCL(KKM) + TOLER(KKM)
452    CALL KALM
453    PDOLAP = 0.0D+0
454    DO 580 IP = 1, NDES
455    PDOLX(IP) = (DABS(XGR(IP) - XM(IP)) + DABS(XM(IP) - X0(IP))) / (1
456    2.0D+TOLER(KKM))
457    IF (PDOLX(IP) .GT. PDOLAP) PDOLAP = PDOLX(IP)
458    PDOLY(IP) = (DABS(YGR(IP) - YM(IP)) + DABS(YM(IP) - Y0(IP))) / (1
459    2.0D+TOLER(KKM))
460    IF (XYRAT*PDOLY(IP) .GT. PDOLAP) PDOLAP = XMRAT*PDOLY(IP)
461    580 CONTINUE
462    CALL RESET(2)
463    C
464    IF (ARCL(KKM) .LT. 0.1D-3) GO TO 605
Listing of TOCALM at 16:46:02 on JUL 23, 1982 for CCid=MU-8'

465 \[ \text{GAMA(KKM)} = \text{GAMA(KKM)} - \text{TOLEG(KKM)} \]
466 \[ \text{CALL KALM} \]
467 \[ \text{DO 590 IP = 1, NDES} \]
468 \[ \text{XO(IP)} = \text{XGR(IP)} \]
469 \[ \text{YO(IP)} = \text{YGR(IP)} \]
470 \[ 590 \text{ CONTINUE} \]
471 \[ \text{CALL RESET(2)} \]
472 \[ \text{GAMA(KKM)} = \text{GAMA(KKM)} + \text{TOLEG(KKM)} \]
473 \[ \text{CALL KALM} \]
474 \[ \text{PDGAP} = 0.0D+0 \]
475 \[ \text{DO 600 IP = 1, NDES} \]
476 \[ \text{PDGX(IP)} = (\text{DABS(XGR(IP)} - \text{XM(IP)}) + \text{DABS(XM(IP)} - \text{XO(IP)}) / ( \]
477 \[ 1.2.0D+0*\text{TOLEG(KKM)}} \]
478 \[ \text{IF (PDGX(IP)} .GT. \text{PDGAP}) \text{PDGAP = PDGX(IP)} \]
479 \[ \text{PDGY(IP)} = (\text{DABS(YGR(IP)} - \text{YM(IP)}) + \text{DABS(YM(IP)} - \text{YO(IP)}) / ( \]
480 \[ 1.2.0D+0*\text{TOLEG(KKM)}} \]
481 \[ \text{IF (XYRAT*PDGY(IP)} .GT. \text{PDGAP}) \text{PDGAP = XYRAT * PDGY(IP)} \]
482 \[ 600 \text{ CONTINUE} \]
483 \[ \text{CALL RESET(2)} \]
484 \[ \text{C} \]
485 \[ 605 \text{IF (ARCL(KKN)} .LT. 0.1D-3) \text{GO TO 645} \]
486 \[ \text{ARCL(KKN)} = \text{ARCL(KKN)} - \text{TOLER(KKN)} \]
487 \[ \text{CALL KALM} \]
488 \[ \text{DO 610 IP = 1, NDES} \]
489 \[ \text{XO(IP)} = \text{XGR(IP)} \]
490 \[ \text{YO(IP)} = \text{YGR(IP)} \]
491 \[ 610 \text{ CONTINUE} \]
492 \[ \text{CALL RESET(2)} \]
493 \[ \text{ARCL(KKN)} = \text{ARCL(KKN)} + \text{TOLER(KKN)} \]
494 \[ \text{CALL KALM} \]
495 \[ \text{PORLAP} = 0.0D+0 \]
496 \[ \text{DO 620 IP = 1, NDES} \]
497 \[ \text{PDORLX(IP)} = (\text{DABS(XGR(IP)} - \text{XM(IP)}) + \text{DABS(XM(IP)} - \text{XO(IP)}) / ( \]
498 \[ 1.2.0D+0*\text{TOLER(KKN)}} \]
499 \[ \text{IF (PDORLX(IP)} .GT. \text{PORLAP}) \text{PORLAP = PDORLX(IP)} \]
500 \[ \text{PDORLY(IP)} = (\text{DABS(YGR(IP)} - \text{YM(IP)}) + \text{DABS(YM(IP)} - \text{YO(IP)}) / ( \]
501 \[ 1.2.0D+0*\text{TOLER(KKN)}} \]
502 \[ \text{IF (XYRAT*PDORLY(IP)} .GT. \text{PORLAP}) \text{PORLAP = XYRAT * PDORLY(IP)} \]
503 \[ 620 \text{ CONTINUE} \]
504 \[ \text{CALL RESET(2)} \]
505 \[ \text{ARCL(KKN)} = \text{ARCL(KKN)} + 1.0D-3 \]
506 \[ \text{C} \]
507 \[ \text{GAMA(KKN)} = \text{GAMA(KKN)} - \text{TOLEG(KKN)} \]
508 \[ \text{CALL KALM} \]
509 \[ \text{DO 630 IP = 1, NDES} \]
510 \[ \text{XO(IP)} = \text{XGR(IP)} \]
511 \[ \text{YO(IP)} = \text{YGR(IP)} \]
512 \[ 630 \text{ CONTINUE} \]
513 \[ \text{CALL RESET(2)} \]
514 \[ \text{GAMA(KKN)} = \text{GAMA(KKN)} + \text{TOLEG(KKN)} \]
515 \[ \text{CALL KALM} \]
516 \[ \text{PORGAP} = 0.0D+0 \]
517 \[ \text{DO 640 IP = 1, NDES} \]
518 \[ \text{PDORGX(IP)} = (\text{DABS(XGR(IP)} - \text{XM(IP)}) + \text{DABS(XM(IP)} - \text{XO(IP)}) / ( \]
519 \[ 1.2.0D+0*\text{TOLEG(KKN)}} \]
520 \[ \text{IF (PDORGX(IP)} .GT. \text{PORGAP}) \text{PORGAP = PDORGX(IP)} \]
521 \[ \text{PDORGY(IP)} = (\text{DABS(YGR(IP)} - \text{YM(IP)}) + \text{DABS(YM(IP)} - \text{YO(IP)}) / ( \]
522 \[ 1.2.0D+0*\text{TOLEG(KKN)}} \]
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523 IF (XYRAT*PDORGY(IP) .GT. PORGAP) PORGAP = XYRAT * PDORGY(IP)
524 640 CONTINUE
525 CALL RESET(2)
526 C  
527 645 CRNKI = CRNKI - TOLEG(KKO)
528 CALL KALM
529 DO 650 IP = 1, NDES
530 XO(IP) = XGR(IP)
531 YO(IP) = YGR(IP)
532 650 CONTINUE
533 CALL RESET(2)
534 CRNKI = CRNKI + TOLEG(KKO)
535 CALL KALM
536 PDCRAP = 0.0D+0
537 DO 660 IP = 1, NDES
538 PDCRX(IP) = (DABS(XGR(IP) - XM(IP)) + DABS(XM(IP) - XO(IP))) / (1.0D+0 + TOLED(KKO))
539 IF (PDCRX(IP) .GT. PDCRAP) PDCRAP = PDCRX(IP)
540 PDCRY(IP) = (DABS(YGR(IP) - YM(IP)) + DABS(YM(IP) - YO(IP))) / (1.0D+0 + TOLED(KKO))
541 IF (XYRAT * PDCRY(IP) .GT. PDCRAP) PDCRAP = XYRAT * PDCRY(IP)
542 660 CONTINUE
543 GO TO 860
544 C  
545 670 GAMA(KKM) = GAMA(KKH) - TOLEG(KKM)
546 CALL KALM
547 DO 680 IP = 1, NDES
548 AO(IP) = AGR(IP)
549 680 CONTINUE
550 CALL RESET(2)
551 GAMA(KKM) = GAMA(KKH) + TOLEG(KKM)
552 CALL KALM
553 PDGAP = 0.0D+0
554 DO 690 IP = 1, NDES
555 PDGA(IP) = (DABS(AGR(IP) - AM(IP)) + DABS(AM(IP) - AO(IP))) / (1.0D+0 + TOLED(KKK))
556 IF (PDGA(IP) .GT. PDGAP) PDGAP = PDGA(IP)
557 690 CONTINUE
558 CALL RESET(2)
559 C  
560 CRNKI = CRNKI - TOLEG(KKO)
561 CALL KALM
562 DO 700 IP = 1, NDES
563 AO(IP) = AGR(IP)
564 700 CONTINUE
565 CALL RESET(2)
566 CRNKI = CRNKI + TOLEG(KKO)
567 CALL KALM
568 PDCRAP = 0.0D+0
569 DO 710 IP = 1, NDES
570 PDCRA(IP) = (DABS(AGR(IP) - AM(IP)) + DABS(AM(IP) - AO(IP))) / (1.0D+0 + TOLED(KKO))
571 IF (PDCRA(IP) .GT. PDCRAP) PDCRAP = PDCRA(IP)
572 710 CONTINUE
573 GO TO 860
574 C  
575 720 IF (ARCL(KKM) .LT. 0.1D-3) GO TO 765
576 ARCL(KKM) = ARCL(KKH) - TOLER(KKM)
Listing of Tocalm at 16:46:02 on JUL 23, 1982 for CCid=MCBB

581 CALL KALM
582 DO 730 IP = 1, NDES
583 RO(IP) = RGR(IP)
584 TO(IP) = TGR(IP)
585 730 CONTINUE
586 CALL RESET(2)
587 ARCL(KKM) = ARCL(KKM) + TOLER(KKM)
588 CALL KALM
589 PDOLAP = 0.0D+0
590 DO 740 IP = 1, NDES
591 PDOLR(IP) = (DABS(RGR(IP) - RM(IP)) + DABS(RM(IP) - RO(IP))) / (1
592 1 2.0D+0*TOLER(KKM))
593 IF (PDOLR(IP) .GT. PDOLAP) PDOLAP = PDOLR(IP)
594 PDOLT(IP) = (DABS(TGR(IP) - TM(IP)) + DABS(TM(IP) - TO(IP))) / (1
595 1 2.0D+0*TOLER(KKM))
596 IF (RTRAT*PDOLT(IP) .GT. PDOLAP) PDOLAP = RTRAT * PDOLT(IP)
597 740 CONTINUE
598 CALL RESET(2)
599 C
600 GAMA(KKM) = GAMA(KKM) - TOLEG(KKM)
601 CALL KALM
602 DO 750 IP = 1, NDES
603 RO(IP) = RGR(IP)
604 TO(IP) = TGR(IP)
605 750 CONTINUE
606 CALL RESET(2)
607 GAMA(KKM) = GAMA(KKM) + TOLEG(KKM)
608 CALL KALM
609 PDOLAP = 0.0D+0
610 DO 760 IP = 1, NDES
611 PDOLR(IP) = (DABS(RGR(IP) - RM(IP)) + DABS(RM(IP) - RO(IP))) / (1
612 1 2.0D+0*TOLER(KKM))
613 IF (PDOLR(IP) .GT. PDOLAP) PDOLAP = PDOLR(IP)
614 PDOLT(IP) = (DABS(TGR(IP) - TM(IP)) + DABS(TM(IP) - TO(IP))) / (1
615 1 2.0D+0*TOLER(KKM))
616 IF (RTRAT*PDOLT(IP) .GT. PDOLAP) PDOLAP = RTRAT * PDOLT(IP)
617 760 CONTINUE
618 CALL RESET(2)
619 C
620 765 IF (ARCL(KKM) .LT. 0.1D-3) GO TO 805
621 ARCL(KKM) = ARCL(KKM) - TOLER(KKM)
622 CALL KALM
623 DO 770 IP = 1, NDES
624 RO(IP) = RGR(IP)
625 TO(IP) = TGR(IP)
626 770 CONTINUE
627 CALL RESET(2)
628 ARCL(KKM) = ARCL(KKM) + TOLER(KKM)
629 CALL KALM
630 PORLAP = 0.0D+0
631 DO 780 IP = 1, NDES
632 PDORLR(IP) = (DABS(RGR(IP) - RM(IP)) + DABS(RM(IP) - RO(IP))) / (1
633 1 (2.0D+0*TOLER(KKM))
634 IF (PDORLR(IP) .GT. PORLAP) PORLAP = PDORLR(IP)
635 PDORLT(IP) = (DABS(TGR(IP) - TM(IP)) + DABS(TM(IP) - TO(IP))) / (1
636 1 (2.0D+0*TOLER(KKM))
637 IF (RTRAT*PDORLT(IP) .GT. PORLAP) PORLAP = RTRAT * PDORLT(IP)
638 780 CONTINUE
CALL RESET(2)

ARCL(KKN) = ARCL(KKN) + 1.0D-3

GAMA(KKN) = GAMA(KKN) - TOLEG(KKN)

CALL KALM

DO 790 IP = 1, NDES
    RO(IP) = RGR(IP)
    TO(IP) = TGR(IP)

790 CONTINUE

CALL RESET(2)

GAMA(KKN) = GAMA(KKN) + TOLEG(KKN)

CALL KALM

DO 800 IP = 1, NDES
    PDORGR(IP) = (DABS(RGR(IP) - RM(IP)) + DABS(RM(IP) - RO(IP)))/
                  (2.0D0 + TOLEG(KKN))
    IF (PDORGR(IP) .GT. PORGAP) PORGAP = PDORGR(IP)
    PDORGT(IP) = (DABS(TGR(IP) - TM(IP)) + DABS(TM(IP) - TO(IP)))/
                  (2.0D0 + TOLEG(KKN))
    IF (RTRAT*PDORGT(IP) .GT. PORGAP) PORGAP = RTRAT*PDORGT(IP)

800 CONTINUE

CALL RESET(2)

CRNKI = CRNKI - TOLEG(KKO)

CALL KALM

DO 810 IP = 1, NDES
    SGR(IP) = SGR(IP)

810 CONTINUE

CALL RESET(2)

CRNKI = CRNKI + TOLEG(KKO)

CALL KALM

PDCRAP = 0.0D+0

DO 820 IP = 1, NDES
    PDCRR(IP) = (DABS(SGR(IP) - SM(IP)) + DABS(SM(IP) - S0(IP)))/
                  (2.0D0 + TOLEG(KKO))
    IF (PDCRR(IP) .GT. PDCRAP) PDCRAP = PDCRR(IP)
    PDCRT(IP) = (DABS(TGR(IP) - TM(IP)) + DABS(TM(IP) - TO(IP)))/
                  (2.0D0 + TOLEG(KKO))
    IF (RTRAT*PDCRT(IP) .GT. PDCRAP) PDCRAP = RTRAT*PDCRT(IP)

820 CONTINUE

GO TO 860

C

830 CRNKI = CRNKI - TOLEG(KKO)

CALL KALM

DO 840 IP = 1, NDES
    SM(IP) = SGR(IP)

840 CONTINUE

CALL RESET(2)

CRNKI = CRNKI + TOLEG(KKO)

CALL KALM

PDCRAP = 0.0D+0

DO 850 IP = 1, NDES
    PDCRS(IP) = (DABS(SGR(IP) - SM(IP)) + DABS(SM(IP) - S0(IP)))/
                  (2.0D0 + TOLEG(KKO))
    IF (PDCRS(IP) .GT. PDCRAP) PDCRAP = PDCRS(IP)

850 CONTINUE

C
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C
860 GO TO (870, 950, 870, 950), MOTH
C
700 870 SUM = 0.0D+0
701 DO 880 NIMRA = 1, IRNUR
702 SUM = SUM + PDAP(MRNUR(NIMRA)) * DSORT(COSTA(MRNUR(NIMRA)))
703 CONTINUE
704 IF (IGNUR .EQ. 0) GO TO 900
705 DO 890 NIMRA = 1, IGNUR
706 SUM = SUM + PGAP(MGNUR(NIMRA)) * DSORT(COSTG(MGNUR(NIMRA)))
707 CONTINUE
708 900 IF (ARCL(KKM) .LT. 0.1D-3) GO TO 903
709 SUM = SUM + PDOLAP * DSORT(COSTA(KKM))
710 1 + PDOGAP * DSORT(COSTG(KKM))
711 903 IF (ARCL(KKN) .LT. 0.1D-3) GO TO 907
712 SUM = SUM + PORLAP * DSORT(COSTA(KKN))
713 1 + PORGAP * DSORT(COSTG(KKN))
714 907 SUM = SUM + PDCRAP * DSORT(COSTG(KKO))
715 IF (MOTH .EQ. 3) OUTOLX = OUTOLR
716 TLA(1) = OUTOLX / DSORT(PDAP(1) * SUM / DSORT(COSTA(1)))
717 DIFA(1) = DABS(TLA(1) * FACTOR - TOLER(1))
718 CONST = TLA(1) * DSORT(COSTA(1))
719 DO 910 NIMRA = 2, IRNUR
720 IZ = MRNUR(NIMRA)
721 TLA(IZ) = CONST * DSORT(DSORT(COSTA(IZ)) / PDAP(IZ))
722 DIFA(IZ) = DABS(TLA(IZ) * FACTOR - TOLER(IZ))
723 CONTINUE
724 IF (IGNUR .EQ. 0) GO TO 930
725 DO 920 NIMRA = 1, IGNUR
726 IZ = MGNUR(NIMRA)
727 TLG(IZ) = CONST * DSORT(DSORT(COSTG(IZ)) / PGAP(IZ))
728 DIFG(IZ) = DABS(TLG(IZ) * FACTOR - TOLER(IZ))
729 CONTINUE
730 IF (ARCL(KKM) .LT. 0.1D-3) GO TO 933
731 TLA(KKM) = CONST * DSORT(COSTA(KKM) / PDOLAP)
732 DIFA(KKM) = DABS(TLA(KKM) * FACTOR - TOLER(KKM))
733 TLG(KKM) = CONST * DSORT(COSTG(KKM) / PDOGAP)
734 DIFG(KKM) = DABS(TLG(KKM) * FACTOR - TOLER(KKM))
735 933 IF (ARCL(KKN) .LT. 0.1D-3) GO TO 937
736 TLA(KKN) = CONST * DSORT(COSTA(KKN) / PORLAP)
737 DIFA(KKN) = DABS(TLA(KKN) * FACTOR - TOLER(KKN))
738 TLG(KKN) = CONST * DSORT(COSTG(KKN) / PORGAP)
739 DIFG(KKN) = DABS(TLG(KKN) * FACTOR - TOLER(KKN))
740 937 TLG(KKO) = CONST * DSORT(COSTG(KKO) / PDCRAP)
741 DIFG(KKO) = DABS(TLG(KKO) * FACTOR - TOLER(KKO))
C
742 CALL COMARC(IREP, TLA, KKL)
743 CALL CORFAC(NDES, KKL, KKM, KKN, KKO)
C
746 IF (NCK .EQ. 2) GO TO 940
747 CALL CHECK(TLA, TLG, TOLER, TOLED, DIFA, DIFG, DEGRAD, KKO,
748 1 ICHECK, MRNUR, IRNUR, MGNUR, IGNUR, MOTH)
749 IF (ICHECK .EQ. 1) GO TO 140
C
750 940 CALL ORDER(TLA, LORDER, KKM)
C
752 CALL RESET(1)
753 CALL RESULT(IREP, ITERN, KKL, KKM, NLOOP, MAXARC, LORDER, TLA,
754 1 KKM, IGNUR, TLG, KKO, NOUTLK, NOUTLP, KLINK, ARCL, GAMA,
LISTING AT TOCALM AT 16:46:02 ON JUL 23, 1982 FOR CCID=MCB8

755 2 MOTN, CLIMIT)

756 C

757 IF (MOTN .EQ. 1) WRITE (7) OUTOLX, OUTOLY, (DEUX(KH), KH=1,NDES),
758 1 (DEVY(JH), JH=1,NDES), (PDX(JH, KH), JH=1,NDES), (PDOLX(JH), KH=1,KKL),
759 2 (PDUX(JH, KH), JH=1,NDES), (PDX(JH), JH=1,NDES), (PDOLX(JH), KH=1, KKL),
760 3 KH=1, KKL), (PDUXY(JH, KH), JH=1,NDES), (PDOLY(JH), KH=1, KKL), (PDUXY(JH),
761 4 JH=1, NDES), (PDOLY(JH), JH=1,NDES), (PDUXY(JH), JH=1,NDES),
762 5 (PDUXY(JH), JH=1,NDES), (PDUXY(JH), JH=1,NDES), (PDUXY(JH), JH=1,NDES),
763 6 (PDUXY(JH), JH=1,NDES), (PDUXY(JH), JH=1,NDES), (PDUXY(JH), JH=1,NDES),
764 7 (PDUXY(JH), JH=1,NDES), (PDUXY(JH), JH=1,NDES),
765 8 (PDUXY(JH), JH=1,NDES)

766 IF (MOTN .EQ. 3) WRITE (7) OUTOLR, OUTOLT, (DEVR(KH), KH=1,NDES),
767 1 (DEVT(JH), JH=1,NDES), (PDR(JH, KH), JH=1,NDES), (PDORL(JH), KH=1, KKL),
768 2 (PDIR(JH, KH), JH=1,NDES), (PDGR(JH, KH), JH=1,NDES),
769 3 KH=1, KKL), (PDGT(JH, KH), JH=1,NDES), (PDOL(JH), JH=1,NDES),
770 4 JH=1, NDES), (PDOL(JH), JH=1,NDES), (PDORL(JH), JH=1,NDES),
771 5 (PDGT(JH, JH=1,NDES), (PDGR(JH, JH=1,NDES),
772 6 (PDIR(JH, JH=1,NDES), (PDORL(JH), JH=1,NDES),
773 7 (PDGR(TJH), JH=1,NDES), (PDORL(JH), JH=1,NDES),
774 8 (PDORL(JH), JH=1,NDES)

775 C

776 WRITE (6,1130)

777 CALL TIME(1, -1, TIM)

778 GO TO 1040

779 C

780 C

781 950 SUM = 0.0D+0

782 DO 960 NIMRA = 1, IRNUR
783 SUM = SUM + PDAP(MRNUR(NIMRA)) * DSORT(COSTA(MRNUR(NIMRA)))

784 960 CONTINUE

785 IF (IGNUR .EQ. 0) GO TO 980

786 DO 970 NIMRA = 1, IGNUR
787 SUM = SUM + PGAP(MGNUR(NIMRA)) * DSORT(COSTG(MGNUR(NIMRA)))

788 970 CONTINUE

789 980 SUM = SUM + PDCRAP * DSORT(COSTG(KKO))

790 IF (MOTN .EQ. 2) SUM = SUM + PDGAP * DSORT(COSTG(KKM))

791 IF (MOTN .EQ. 2) TOLAS = OUTOLA * DEGRAD

792 IF (MOTN .EQ. 4) TOLAS = OUTOLS

793 TLA(1) = TOLAS / DSORT(PDAP(1)*SUM/DSORT(COSTA(1)))* DSORT(FACTOR - TOLER(1))

794 DIFA(1) = DABS(TLA(1)) * DSORT(TLA(1)) / DSORT(COSTA(1))

795 CONST = TLA(1) * DSORT(PDAP(1)/DSORT(COSTA(1)))

796 DO 990 HIMRA = 2, IRNUR
797 IZ = MRNUR(HIMRA)
798 TLA(IZ) = CONST * DSORT(COSTA(IZ)) / DSORT(PDAP(IZ))
799 DIFA(IZ) = DABS(TLA(IZ)) * DSORT(TLA(IZ)) / DSORT(FACTOR - TOLER(IZ))

800 990 CONTINUE

801 IF (IGNUR .EQ. 0) GO TO 1010

802 DO 1000 NIMRA = 1, IGNUR
803 IZ = MGNUR(NIMRA)
804 TLG(IZ) = CONST * DSORT(COSTG(IZ)) / DSORT(PGAP(IZ))
805 DIFG(IZ) = DABS(TLG(IZ)) * DSORT(FACTOR - TOLER(IZ))

806 1000 CONTINUE

807 1010 IF (MOTN .EQ. 4) GO TO 1020

808 TLG(KKM) = CONST * DSORT(COSTG(KKM)) / DSORT(PDAP)
809 DIFG(KKM) = DABS(TLG(KKM)) * DSORT(FACTOR - TOLER(KKM))

810 1020 TLG(KKO) = CONST * DSORT(COSTG(KKO)) / DSORT(PDCRAP)
811 DIFG(KKO) = DABS(TLG(KKO)) * DSORT(FACTOR - TOLER(KKO))

812 C
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CALL COMARC(IREP, TLA, KKL)
CALL CORFAC(NDES, KKL, KKM, KKN, KKO)

C
IF (NCK .EQ. 2) GO TO 1030
CALL CHECKTLA, TLG, TOLER, TOLEG, TOL6D, DIFA, DIFG, DEGRAD, KKO,
1 ICHECK, KRNUR, IINR, MGNUR, IGNUR, IOTN)
IF (ICHECK .EQ. 1) GO TO 140
C
1030 CALL ORDER(TLA, LORDER, KKL)
CALL RESET(I)
CALL RESULT(IREP, ITERN, KKL, KKM, NLOOP, NOUTL, NOUTL, KLINK, ARCL, GAMA,
1 KKN, IGNUR, TLE, KKO, IPOUT, NOUT, KLINK, ARCL, GAMA,
2 MOTN, CLIMIT)
C
IF (MOTN .EQ. 2) WRITE (7) OUTOLA, (DEVA(KH), KH=1, NDES),
1 ((PDA(JH, KH), JH=1, NDES), KH=1, KKL), ((PDGA(JH, KH), JH=1, NDES),
2 KH=1, KKL), (PDGA(JH), JH=1, NDES), (PDCRA(JH), JH=1, NDES)
1040 IF (LAST .EQ. 0) GO TO 10
STOP
C
1050 FORMAT (18A4)
1060 FORMAT (1H1/" ================================" /* ***/
1 /** TOCALM : OSMAN : FEB 82 /** */ */
2 */ ***/ ================================, 1X, 18A4)
1070 FORMAT (/5X, 'LINEAR DIMENSIONS ARE IN MILLIMETERS')
1080 FORMAT (/5X, 'LINEAR DIMENSIONS ARE IN INCHES')
1110 FORMAT (/5X, 'OUTPUT TOLERANCE (SLIDER DISPLACEMENT)=', E9.3)
1120 FORMAT (/5X, 'EXECUTION TIME')
1130 FORMAT (///5X, 'EXECUTION TIME')
1140 FORMAT (1H1)
END
C
C
SUBROUTINE RESET(NM)
C
---
C
IMPLICIT REAL*8(A - H, O - Z)
C
COMMON ARCL(100), AARCL(100), GAMA(100), GGAMA(100), DEGINC,
1 IKON(361), ILINK(100), ILOOP(100), ITITLE(18), IPTLOT, KKL,
2 KKRM, KKN, KKO, MAXARC, NLOOP, NFORM, NPOINT, MOTN, IANG,
3 MOTION, NDES, KON, IILINK(100), ILOOP(100), KLINK(100)
C
DO 10 I = 1, KKL
10 ILOOP(I) = IILoop(I)
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10 CONTINUE
872 IF (NM .EQ. 1) GO TO 30
873 DO 20 I = 1, KKL
874 ILINK(I) = ILINKM
875 20 CONTINUE
876 GO TO 50
877 DO 40 I = 1, KKL
878 ILINKM = ILINKM
879 40 CONTINUE
880 50 CONTINUE
881 60 CONTINUE
882 RETURN
883 END

C
884 C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * C
885 C SUBROUTINE KALM
886 C -----------------------------------------------
887 C IMPLICIT REAL*8(A - H, O - Z)
888 C DIMENSION LAF(3), ILHD(10), IGH(10), LAN(7), DESX(37), DESY(37),
889 1 DESANG(37), ANMULT(37), XMULT(37), YMULT(37), OPLOW(30),
890 2 OPHIGH(30), IVA(IO), IVG(IO)
891 C COMMON ARCL(100), AARCL(100), GAMA(100), GGAMA(100), DEGINC,
892 1 IKOM(361), ILINK(100), IPRT(10), IPOP(10), IPOP2, IPOP3,
893 2 KKN, KKM, KKK, MAXRC, MLOOP, NFORM, NPOINT, MOTOR, IANG,
894 3 MOTION, NDES, KON, ILINK(100), ILINK(100), KLIFK(100)
895 COMMON /XYZNUR/ XGR(37), YGR(37), SGR(37), AGR(37), RGR(37),
896 1 TGR(37)
897 COMMON /REST/ CONFIG(10), DELT(361), SLIDE(10), CRNKI, HPI, PI,
898 1 DEGRAD, RINC, TUSTA, IJOIN(10), LARCD(100), LARC(100),
899 2 LARCX(20), LOOPL(10), KOL, KOL(5), KTHETA, LBA, LKFIN,
900 3 LKOUT, LKR, LKRET, NOVER, NROOT, NOUTL, NOUTK,
901 4 NOUTL, IDEL, IDELV, IDEL, IVEL, IACC, LCCL(5), TANGLE
902 EQUIVALENCE (DESX(I), DESY(I), DESANG(I), ANMULT(I), XMULT(I), YMULT(I)
903 1 , OPLOW(I), OPHIGH(I), (IKOM(I), IVA(I), IVG(I)))
904 C
905 CALL SETUP
906 C
907 DO 10 I = 1, KKL
908 IF (ILOOP(I) .LT. 0) ARCLM = -0.00001
909 10 CONTINUE
910 C
911 IF (MOTOR) 30, 30, 20
912 20 ARCL(KK) = CRNKI
913 GO TO 50
914 C
915 IF (MOTION .LE. 3) GO TO 50
916 IF (MOTION .LE. 3) GO TO 40
917 40 ARCL = MOTION
918 50 NLP(1) = (NOUTL - 1) * MAXARC
919 IF (NOUTL .LT. 0) GO TO 60
920 LKOUT = NLP + NOUTL
921 LKRET = LKOUT + 1

10 CONTINUE
11 IF (MOTOR) 30, 30, 20
12 20 ARCL(KK) = CRNKI
13 GO TO 50
14 C
15 IF (MOTION .LE. 3) GO TO 50
16 IF (MOTION .LE. 3) GO TO 40
17 40 ARCL = MOTION
18 50 NLP(1) = (NOUTL - 1) * MAXARC
19 IF (NOUTL .LT. 0) GO TO 60
20 LKOUT = NLP + NOUTL
21 LKRET = LKOUT + 1
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164

C MOUTLK = NOUTLK
930   GO TO 70
931   60 LKOUT = NLPOUT - NOUTLK
932   LKRET = LKOUT
933   MOUTLK = -NOUTLK
934   70 LKR = LKRET - 1
935   C
936   C   SORT OUT LAYOUT FOR RESULTS
937   C
938   C   I = IANG + 1
939   C   80 LBA = 3
940   C   GO TO 100
941   C   90 LBA = 1
942   C   100 KOL = 2
943   C   NFORM = 1
945   C   GO TO 120
946   C   110 LBA = 2
947   C   KOL = 3
948   C   NFORM = 7
949   C   120 NCOL = 11 / KOL
950   C
951   C   INPUT LINK ANGLES FOR ANALYSIS
952   C
953   C   IF (NDES .GT. 0) GO TO 130
954   C   IF (NPOINT .GT. 0) GO TO 140
955   C   GO TO 240
956   C   130 IF (NPOINT .EQ. 0) IDEL = 1
957   C   NPOINT = NDES
958   C   140 IF (IDEL .NE. 0) GO TO 160
959   C   IF (MOTOR .LE. 0) GO TO 150
960   C   GO TO 240
961   C   150 POINT = NPOINT
962   C   DEGINC = 360.0 / POINT
963   C   RINC = DSIGN(DEGINC,CRNKD)
964   C   GAMAUKO) = CRNKI - RINC
965   C   NPOINTE = NPOINTE + 1
966   C   160 MOVER = 1
967   C   NLCOL = (NPOINTE + NCOL - 1) / NCOL
968   C   NKOL = NCOL * KOL
969   C   KOLA = KOL - NKOL * NLCOL
970   C   NP = NPOINTE * KOL
971   C   NCOL = NPOINTE - NCOL * (NLCOL - 1)
972   C   DO 170 1 = 1, NLCOL
973   C   KOLL(I) = (I - 1) * KOLA
974   C   170 LCOL(I) = I * NLCOL
975   C   IF (NCOL .EQ. NCOL) GO TO 190
976   C   NHCOL = I + NLCOL
977   C   NKOLA = NKOL + KOLA
978   C   NKOLB = -NLCOL * NKOL
979   C   DO 180 I = NHCOL, NCOL
980   C   KOLL(I) = (I - 1) * NKOLA + NKOLB
981   C   180 LCOL(I) = I * (NLCOL - 1) + NLCOL
982   C   190 NFROUT = NLPOUT + LOOPU(NOUTLP)
983   C   LKFIN = NFROUT - 1
984   C
985   C   CHANGE ANGLE OF LAST FRAME ARC IN EACH LOOP
986   C   FROM RELATIVE TO FRAME ARC IN FIRST LOOP TO RELATIVE TO X-AXIS
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987  C
988  IFR = LOOPL(1)
989  GAMAM(IFR) = GAMAM(IFR) - 180.0
990  IF (NLOOP .EQ. 1) GO TO 220
991  DO 210 L = 2, NLOOP
992      I = (L - 1) * MAXARC + LOOPL(L)
993      JJ = I
994  200  J = LARCD(JJ)
995  GAMAM(I) = GAMAM(I) + GAMAM(J)
996  IF (MOD(J,MAXARC) .EQ. IFR) GO TO 210
997  IF (JJ .EQ. J) GO TO 240
998      JJ = J
999  GO TO 200
1000  210 CONTINUE
1001  220 CONTINUE
1002  DO 230 L = 2, NLOOP
1003       J = LARCD(JJ)
1004       GAMAM = GAMAM - GAMAM(J)
1005       IF (MOD(J,MAXARC) .EQ. IFR) GO TO 210
1006       IF J = J GO TO 240
1007       JJ = J
1008  210 CONTINUE
1009  220 CONTINUE
1010  230 CONTINUE
1011  240 RETURN
1012  END
1013  C
1014  C
1015  C
1016  C
1017  C
1018  C
1019  C
1020  C
1021  C
1022  C
1023  C
1024  C
1025  C
1026  C
1027  C
1028  C
1029  C
1030  C
1031  C
1032  C
1033  C
1034  C
1035  C
1036  C
1037  C
1038  C
1039  DO 500 I = 1, NLOOP
1040      ISWAP = 0
1041      LLOOP(I) = 0
1042      IND = (I - 1) * MAXARC
1043      DO 460 J = 1, MAXARC
1044          INDEX = J + IND
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1045 INDLK = ILINK(INDEX)
1046 INDLP = ILOOP(INDEX)
1047 IDENT(INDEX) = 0
1048 LARCD(INDEX) = 0
1049 LARCF(INDEX) = 0
1050 IF (INDLP) 10, 50, 360
1051 10 IF (INDEX - 2) 340, 460, 20
1052 20 IPRLP = ILOOP(INDEX - 1)
1053 IPRLK = ILINK(INDEX - 1)
1054 IF (IPRLP) 30, 40, 460
1055 30 IJUMP = 1
1056 IF (INDLP .EQ. (1 - J)) GO TO 110
1057 IF (IPRLP .EQ. - J) GO TO 100
1058 GO TO 90
1059 40 IJUMP = 2
1060 ISWAP = 1
1061 IF (-IABS(IPRLK) .EQ. INDLP) GO TO 150
1062 GO TO 130
1063 50 IF (INDLK .EQ. 0) GO TO 160
1064 IF (INDEX - 2) 350, 460, 60
1065 60 IPRLP = ILOOP(INDEX - 1)
1066 IPRLK = ILINK(INDEX - 1)
1067 IF (IPRLP) 70, 80, 460
1068 70 IJUMP = 2
1069 60 TO 140
1070 GO TO 120
1071 C-----THREE REVOLUTE JOINTS
1072 80 IJOINT(I) = 1
1073 JOINT(I) = 1
1074 IJUMP = 1
1075 GO TO 170
1076 C-----TWO SLIDERS ON DETERMINED LINKS
1077 90 IJOINT(I) = 2
1078 JOINT(I) = 8
1079 GO TO 250
1080 C-----TWO SLIDERS ON FOLLOWING UNDETERMINED AND DETERMINED LINKS
1081 100 IJOINT(I) = 3
1082 JOINT(I) = 6
1083 GO TO 250
1084 C-----TWO SLIDERS ON PRECEDING DETERMINED AND UNDETERMINED LINKS
1085 110 IJOINT(I) = 4
1086 JOINT(I) = 7
1087 GO TO 250
1088 C-----SLIDER ON PRECEDING DETERMINED LINK
1089 120 IJOINT(I) = 5
1090 JOINT(I) = 5
1091 GO TO 250
1092 C-----SLIDER ON FOLLOWING DETERMINED LINK
1093 130 IJOINT(I) = 5
1094 JOINT(I) = 4
1095 GO TO 170
1096 C-----SLIDER ON FOLLOWING UNDETERMINED LINK
1097 140 IJOINT(I) = 6
1098 JOINT(I) = 2
1099 GO TO 250
1100 C-----SLIDER ON PRECEDING UNDETERMINED LINK
1101 150 IJOINT(I) = 6
1102 JOINT(I) = 3
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1103  GO TO 170
1104  C-----NON-EXISTENT ARCS
1105     160 IF (LOOPL(I) .EQ. 0) LOOPL(I) = J - 1
1106     GO TO 460
1107  C-----FIRST REVOLVE JOINT
1108  170 IF (IPRLK) 180, 460, 190
1109     180 SLIDE(I) = 1.0
1110     GO TO 200
1111     190 SLIDE(I) = -1.0
1112     200 IUNKNO = IUNKNO + 1
1113     LARCX(IUNKNO) = J - 1
1114     NJOINT = NJOINT + 1
1115     NLINK = NLINK + 4
1116     GO TO (210, 290), IJUMP
1117  C-----SECOND REVOLVE JOINT
1118  210 IF (INDLK) 220, 460, 230
1119     220 CONFIG(I) = 1.0
1120     GO TO 240
1121     230 CONFIG(I) = -1.0
1122     240 IUNKNO = IUNKNO + 1
1123     LARCX(IUNKNO) = J
1124     IF (ISWAP) 460, 460, 330
1125  C-----FIRST SLIDER
1126  250 IF (IPRLK) 260, 460, 270
1127     260 SLIDE(I) = HPI
1128     270 SLIDE(I) = -HPI
1129     280 IUNKNO = IUNKNO + 1
1130     LARCX(IUNKNO) = J
1131     LARCX(IUNKNO) = -1
1132     IF (ISVAP) 460, 460, 330
1133     INDEX = INDEX - 1
1134     LARCD(INDEX) = IND - IPRLP
1135     LARCF(INDEX) = -1
1136     GO TO (290, 210), IJUMP
1137  C-----SECOND SLIDER
1138  290 IF (INDLK) 300, 460, 310
1139     300 CONFIG(I) = HPI
1140     320 CONFIG(I) = -HPI
1141     320 IUNKNO = IUNKNO + 1
1142     LARCX(IUNKNO) = J
1143     LARCX(INDEX) = IND - INDLK
1144     LARCF(INDEX) = -1
1145     IF (ISWAP) 460, 460, 330
1146     SLST = SLIDE(I)
1147     SLIDE(I) = -CONFIG(I)
1148     CONFIG(I) = -SLST
1149     LARCX(IUNKNO - 1) = J
1150     LARCX(IUNKNO) = J - 1
1151     GO TO 460
1152  C-----SLIDING INPUT LINK
1153     PRISM = -INDLK
1154     GAMAKKO = DSIGN(90.0, PRISM)
1155     MOTOR = 1
1156     INDLK = 1
1157     GO TO 450
1158  C-----SPATIAL ROTARY INPUT
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1161          350  MOTOR = -1
1162          360  GO TO 450
1163 C-----DETERMINED ARC
1164          370  IF (INDLP .LT. 1) GO TO 370
1165          380  IF (I .EQ. 1) GO TO 370
1166          390  IERR = 1
1167          400  IF (INDLK) 420, 460, 380
1168 C-----DOUBLE JOINT
1169          410  IF (I .EQ. 1) GO TO 440
1170          420  INDST = (INDLP - 1) * MAXARC + INDLK
1171          430  IF (IDENTA(INDSI) .EQ. 0) IDENTA(INDSI) = INDST
1172          440  IDLNK = IDENTA(INDSI)
1173          450  IDENTA(INDEX) = IDLNK
1174          460  IF (GAMA(INDEX) .EQ. 0 .AND. ARCL(INDEX) .EQ. ARCL(INDSI))
1175          470  IWARN = 1
1176          480  IF (LARCD(INDST) EQ. 0) GO TO 410
1177 C-----TERNARY LINK WITH DOUBLE JOINT
1178          490  LARCD(INDEX) = IDLNK
1179          500  INDSI = (INDLP - I) * MAXARC + INDLK
1180          510  IF (IDENTA(INDSI) .EQ. 0) IDENTA(INDSI) = INDST
1181          520  IDLNK = IDENTA(INDSI)
1182          530  IDENTA(INDEX) = IDLNK
1183          540  GO TO 460
1184 C-----BINARY LINK WITH DOUBLE JOINT
1185          550  INDSI = (INDLP - 1) * MAXARC
1186          560  LARCD(INDEX) = INDLK
1187          570  LARCF(INDEX) = INDLK * LOOPL(INDLP)
1188          580  GO TO 460
1189 C-----TERNARY LINK
1190          590  INDSI = (INDLP - 1) * MAXARC
1191          600  NLINK = NLINK + 1
1192          610  NJOINT = NJOINT + 1
1193          620  INDSI = INDLK - INDLK
1194          630  LARCD(INDEX) = INDST
1195          640  IF (-INDLK .GT. LOOPL(INDLP)) GO TO 430
1196          650  IF (ARCL(INDEX) .NE. ARCL(INDSI)) GO TO 460
1197          660  IF (DABS(GAMA(INDEX) - 180.00) .GT. 1.0D-12) GO TO 460
1198          670  NINDLK = -INDLK
1199          680  IWARN = 1
1200          690  IF (IDENTA(INDSI) .EQ. 0) IDENTA(INDSI) = INDST
1201          700  IDENTA(INDEX) = IDENTA(INDSI)
1202          710  NJOINT = NJOINT - 1
1203          720  NLINK = NLINK - 1
1204          730  GO TO 460
1205          740  CONTINUE
1206 C-----PLANAR ROTARY INPUT
1207          750  CONTINUE
1208          760  CONTINUE
1209          770  CONTINUE
1210          780  CONTINUE
1211          790  CONTINUE
1212          800  CONTINUE
1213          810  CONTINUE
1214          820  CONTINUE
1215          830  CONTINUE
1216          840  CONTINUE
1217          850  CONTINUE
1218          860  CONTINUE
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1219 IF (L2U - 1 .EQ. L1U) GO TO 470
1220 IF (L1U - 1 .EQ. L2U) GO TO 470
1221 IERR = 1
1222 470 IND2 = I + I
1223 IERR = 1
1224 480 CONTINUE
1225 IF (LOOPL(I) .EQ. 0) LOOPL(I) = MAXARC
1226 JST = IND + 1
1227 JFN = IND + LOOPL(I)
1228 DO 490 J = JST, JFN
1229 IF (LARCF(J) .EQ. -1) LARCF(J) = JFN
1230 490 CONTINUE
1231 500 CONTINUE
1232 C
1233 IDENTIFY ALL SLIDING,PRISMATIC LINKS BY NEGATIVE ENTRY IN ILOOP
1234 TO PICK UP THOSE LINKS IN ERROR, PLACE 'SOURCE' ARCS IN ILINK
1235 C
1236 510 DO 520 I = 1, KKL
1237 IF (ILOOP(I) .GT. 0) ILOOP(I) = 0
1238 520 CONTINUE
1239 DO 540 I = 1, KKL
1240 IDLNK = IDENTA(I)
1241 IF (IDLNK .GT. 0) GO TO 530
1242 ILINK(I) = 1
1243 GO TO 540
1244 530 ILINK(I) = IDLNK
1245 ILOOP(I) = ILOOP(IDLNK)
1246 540 CONTINUE
1247 RETURN
1248 C
1249 END
1250 C
1251 *******************************
1252 C
1253 SUBROUTINE SOLVE
1254 C -----
1255 C CALCULATE KINEMATICS
1256 C
1257 IMPLICIT REAL*8(A - H, O - Z)
1258 DIMENSION THET(100), THD(100), TH2D(100), ARCLD(100),
1259 1 ARCL2D(100), LAF(3), LAN(7), ILHD(10), ITHD(10),
1260 2 MVIO(5), LAG(3), LAH(3)
1261 COMMON ARCL(100), AARCL(100), GAMA(100), GGAMA(100), DEGINC,
1262 1 IKON(361), ILINK(100), LOOPL(100), TITLE(18), IPLOT, KKL,
1263 2 KKK, KKK, KK, MAXARC, NLOOP, NFORM, NPOINT, MOTOR, IAMG,
1264 3 MOTION, NDOS, KON, ILINK(100), ILOOP(100), KLINK(100)
1265 COMMON /APART/ JNT, J, M, MS, NPT
1266 COMMON /XYZNUR/ XGR(37), YGR(37), SGR(37), AGR(37), RGR(37),
1267 1 TGR(37)
1268 COMMON /REST/ CONFIG(10), DELT(361), SLIDE(10), CRuki, HPI, PI,
1269 1 DEGRAD, RINC, TWSTA, IJOIN(10), LARCD(100), LARCF(100),
1270 2 LARCX(20), LOOPL(10), KOL, KOLL(5), KTETA, LBA, LKFIN,
1271 3 LKOUT, LKR, LKRET, MOVER, NFROUT, NKOL, NLM, NOTLK,
1272 4 NOUTLP, IDEL, IDELV, IDEL, IVE, IACC, LCOL(5), TANGE
1273 EQUIVALENCE (MVIO(1),IJWT)
1274 ITANG = 0
1275 IK = 1
1276 KOLIN = KOLL(I)
LCOLN = LCOL(1)
DO 10 I = 1, KKL
10 THETA(I) = 0
OUTL = ARCL(KKM)
ORIL = ARCL(KKM)
OUTANG = GAMA(KKM)
ORIGN = GAMA(KKM)
AFR = ARCL(NFROUT)
GFR = GAMA(NFROUT)
GFRPI = GFR - PI
XFR = AFR * DCOS(GFR) + ORIL
YFR = AFR * DSIN(GFR) + ORIL
OUTRAD = OUTANG + GFR
OUTDEG = OUTRAD / DEGRAD
C
C THE KINEMATICS
C
IFR = LOOPL(1)
GREF = GAMA(IFR) / DEGRAD
IF (MOTOR) 30, 60, 20
C-----SLIDING LINK INPUT
20 THETI = GAMA(KKO) / DEGRAD
ARCLI = ARCL(KKO)
ASSIGN 200 TO LB150
DEGINC = 1.0
GO TO 90
C-----SPATIAL ROTARY INPUT
30 THETI = HPI - GAMA(IFR)
ARCLI = ARCL(1)
ARCL2 = ARCL(2)
OFFSET = ARCL(KKO + 1)
CRANKI = GAMA(KKO)
IF (IDEL .NE. 0) GO TO 40
ASSIGN 120 TO LB150
ASSIGN 180 TO LB160
GO TO 50
40 DEGINC = 1.0
ASSIGN 140 TO LB150
50 ASSIGN 170 TO LB160
GO TO 90
C-----PLANAR ROTARY INPUT
60 CRANKI = GAMA(KKO) - GREF
IF (IDEL .NE. 0) GO TO 70
ASSIGN 110 TO LB150
ASSIGN 180 TO LB160
GO TO 80
70 DEGINC = 1.0
ASSIGN 160 TO LB150
80 ASSIGN 170 TO LB160
90 CONTINUE
ASSIGN 250 TO LB260
C
C INDEX INPUT LINK TO SPECIFIED ANGLES OR LENGTHS
C
DO 590 NPT = 1, NPOINT
. IF (NPT .LE. LCOLN) GO TO 100
IK = IK + 1
Kolin = Koll(IK)
LCOLN = LCOL(IK)
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1335 100 KON = (NPT - 1) * NKOL + 1 + KOLIN
1336 IKON(NPT) = KON
1337 GO TO LB150, (110, 120, 130, 140, 200)
1338 C
1339 C ROTATING LINK INPUT
1340 C
1341 110 POINT = NPT
1342 CRANK = CRANK1 + POINT * RINC
1343 GO TO 150
1344 120 POINT = NPT
1345 CRANKF = CRANK1 + POINT * RINC
1346 CRANK = CRANKF * DEGRAD
1347 GO TO 160
1348 130 CRANKF = CRANK1 + DELT(NPT)
1349 CRANK = CRANKF * DEGRAD
1350 GO TO 160
1351 140 CRANKF = CRANK1 + DELT(NPT)
1352 CRANK = CRANKF * DEGRAD
1353 150 IF (CRANKF LT. 0) CRANKF = CRANKF + 360.0
1354 IF (CRANKF AT. 360.0) CRANKF = CRANKF - 360.0
1355 GO TO LB160, (170, 180)
1356 170 THETA(MOVER) = CRANK * DEGRAD
1357 GO TO 210
1358 C
1359 C SPATIAL ROTARY INPUT
1360 C
1361 180 THETA(MOVER) = THE1
1362 SCRA = DSIN(CRANK)
1363 CCRA = DCOS(CRANK)
1364 ASC1 = ARCL1 * SCRA
1365 ARCL(1) = ASC1
1366 ACC1 = ARCL1 * CCRA
1367 OFFS = OFFSET - ACC1
1368 IF (ARCL2 GT. DABS(OFFS)) GO TO 190
1369 IJNT = 1
1370 J = 1
1371 M4 = 2
1372 M5 = 3
1373 GO TO 550
1374 190 ARCLT = DSQRT(ARCL2*ARCL2 OFFS*OFFS)
1375 ARCL(2) = ARCLT
1376 GO TO 210
1377 C
1378 C SLIDING LINK INPUT
1379 C
1380 200 ARC = ARCL1 + DELT(NPT)
1381 ARCL(MOVER) = ARC
1382 210 ASSIGN 220 TO LB220
1383 C
1384 C ANALYZE EACH LOOP IN TURN
1385 C
1386 DO 480 J = 1, NLOOP
1387 M1 = (J - 1) * MAXARC
1388 M11 = M1 + LOOPL(J)
1389 M = J + J
1390 M2 = LARCX(MU - 1)
1391 M3 = LARCX(MU)
1392 M4 = M1 + M2
Listing of TOCALM at 16:46:02 on JUL 23, 1982 for CCid=MCB8

1393  M5 = M1 + M3
1394  THETA(M11) = PI
1395  GM11 = GAMMA(M11)
1396  C1 = -ARCL(M11)
1397  C2 = 0
1398  L = LOOPL(J) - 1
1399  C
1400  C  SUMMATE THE DETERMINED ARCS FOR THE LOOP
1401  C
1402  DO 250 I = 1, L
1403    IF (I .EQ. M2 OR. I .EQ. M3) GO TO 250
1404    M11 = M1 + I
1405    GO TO LB220, (220v 230)
1406  220  ASSGN 230 TO LB220.
1407  11 = 1
1408  13 = 1
1409  DO 240
1410  230  I2 = LARCF(M11)
1411  13 = LARCD(M11)
1412  THETA(M11) = THETA(13) + GAMMA(M11) - (GM11 - GAMMA(12))
1413  11 = ILINK(M11)
1414  ARCL(M11) = ARCL(11)
1415  240  ALM11 = ARCL(M11)
1416  THM11 = THETA(M11)
1417  CTHM = DCOS(THM11)
1418  STHM = DSIN(THM11)
1419  C11 = ALM11 * CTHM
1420  C21 = ALM11 * STHM
1421  C1 = C1 + C11
1422  C2 = C2 + C21
1423  250 CONTINUE
1424  C
1425  C  CALCULATE THE UNDETERMINED DYAD
1426  C
1427  IJNT = IJOINT(J)
1428  GO TO (420, 260, 280, 290, 310, 350), IJNT
1429  C
1430  C  TWO PRISMATIC JOINTS, ONE REVOLUTE JOINT
1431  C
1432  C-----TWO SLIDERS ON KNOWN LINKS
1433  260  I1 = LARCD(M4)
1434  THM4 = THETA(I1) - SLIDE(J)
1435  I2 = LARCD(M5)
1436  THM5 = THETA(I2) + CONFIG(J)
1437  SINDTH = DSIN(THM4 - THM5)
1438  IF (DABS(SINDTH) .LT. 1.0D-12) GO TO 270
1439  NCOUNT = IJNT
1440  GO TO 550
1441  270  THETA(M4) = THM4
1442  THETA(M5) = THM5
1443  STHMS = DSIN(THM5)
1444  CTHM5 = DCOS(THM5)
1445  STHM5 = DSIN(THM4)
1446  CTHM4 = DCOS(THM4)
1447  CSPM4 = CTHM4 + STHM4
1448  CSPM5 = CTHM5 + STHM5
1449  ST21 = -SINDTH
1450  CCCS = C2 * CTHM5 - C1 * STHM5
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1451 ALM4 = CCCS / ST21
1452 ALM5 = -(C1 + C2 + ALM4*CSPM4) / CSPM5
1453 ARCL(M4) = ALM4
1454 ARCL(M5) = ALM5
1455 GO TO 480
1456 C-----TWO SLIDERS ON FOLLOWING UNDETERMINED AND DETERMINED ARCS
1457 280 I2 = LARCD(M5)
1458 THMS = THETA(I2) + CONFIG(J)
1459 THM4 = THM5 + SLIDE(J)
1460 SINDTH = DSIGN(1.0D0,SLIDE(J))
1461 GO TO 300
1462 C-----TWO SLIDERS ON PRECEDING DETERMINED AND UNDETERMINED ARCS
1463 290 I2 = LARCD(M4)
1464 THM4 = THETA(I2) - SLIDE(J)
1465 THM5 = THM4 - CONFIG(J)
1466 SINDTH = DSIGN(1.0D0,CONFIG(J))
1467 300 THETA(M4) = THM4
1468 THETA(M5) = THM5
1469 STHM4 = DSIN(THM4)
1470 CTHM5 = DCOS(THM5)
1471 ARCL(M4) = -SINDTH * (C2*CTHM5 - C1*STHM5)
1472 ARCL(M5) = -(C1*CTHM5 + C2*STHM5)
1473 GO TO 480
1474 C
1475 C ONE PRISMATIC JOINT, TWO REVOLUTE JOINTS
1476 C
1477 C-----SLIDER ON DETERMINED ARC
1478 310 ARCL5 = ARCL(M5)
1479 I1 = LARCD(M4)
1480 THM4 = THETA(I1) - SLIDE(J)
1481 THETA(M4) = THM4
1482 STHM4 = DSIN(THM4)
1483 CTHM4 = DCOS(THM4)
1484 C3 = C1 * STHM4 - C2 * CTHM4
1485 C4 = ARCL5 * STHM4
1486 C5 = -ARCL5 * CTHM4
1487 IF (DABS(STHM4) GT. 0.001) GO TO 320
1488 SINDTH = C2 / ARCL5
1489 SINDTH = DABS(SINDTH)
1490 IF (SINDTH .GT. 1.0) GO TO 320-
1491 THMS = THM4 - DSIGN(HPI,C2) - CONFIG(J) * (DARCOS(SINDTH))
1492 THM5 = (THMS - PI - PI) * CTHM4
1493 STHM5 = DSIN(THM5)
1494 CTHM5 = DCOS(THM5)
1495 THETA(M5) = THM5
1496 GO TO 410
1497 320 ARG = (ARCL5 + C3) * (ARCL5 - C3)
1498 CFS = ARCL5 - DABS(C3)
1499 C6 = ARCL5 * ARCL5
1500 IF (CFS) 340, 330, 380
1501 C-----FIXED ARC ON LIMIT
1502 330 ALN2 = C1 * CTHM4 + C2 * STHM4
1503 ARCL(M4) = ALN2
1504 CSPM4 = CTHM4 + STHM4
1505 SINK5 = C3 * CTHM4 / ARCL5
1506 COSM5 = -(C3 + C5*SINK5) / C4
1507 CSPM5 = CTHM5 + STHM5
1508 THETA(M5) = DATAN2(SINK5,COSM5)
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1509 GO TO 480
1510 C-----FIXED LENGTH ARC TOO SHORT
1511 SHORT = -CFS
1512 GO TO 550
1513 C-----SLIDER ON UNDETERMINED ARC
1514 ARCL5 = ARCL(M5)
1515 CFS = C1 * C1 + C2 * C2
1516 PSEUDO = DSORT(CFS)
1517 IF (DABS(C1) .GT. 0.001) GO TO 360
1518 COSDTH = ARCL5 / PSEUDO
1519 IF (DABS(COSDTH) .GT. 1.0) GO TO 360
1520 THM5 = DATAN2(-C2, -C1) - CONFIG(J) * DARCOS(COSDTH)
1521 STHM5 = DSIN(THM5)
1522 CTHM5 = DCOS(THM5)
1523 THETA(M5) = THM5
1524 GO TO 410
1525 360 CF = CF --
1526 C5 = C2
1527 C6 = CFS
1528 C3 = ARCL5
1529 ARG = CFS - C3 * C3
1530 ARBS = PSEUDO - C3
1531 IF (ARBS) 550, 370, '380
1532 C-----GUIDE ON LIMIT
1533 ARCL(M4) = 0
1534 C1' = -C1
1535 THM5 = -DATAN2(C2, C1)
1536 STHM5 = DSIN(THM5)
1537 CTHM5 = DCOS(THM5)
1538 GO TO 390
1539 C-----GUIDE TOO LONG
1540 STHM5 = (-C3*C5 + CONFIG(J)*C4*DSORT(ARG)) / C6
1541 CTHM5 = -(C3 + C5*STHM5) / C4
1542 THM5 = DATAN2(STHM5, CTHM5)
1543 390 THETA(M5) = THM5
1544 400 IF (IJNT .EQ. 5) GO TO 410
1545 THM4 = THETA(M5) + SLIDE(J)
1546 STHM4 = DSIN(THM4)
1547 CTHM4 = DCOS(THM4)
1548 THETA(M4) = THM4
1549 410 CONTINUE
1550 CSPM5 = CTHM5 + STHM5
1551 CSPM4 = CTHM4 + STHM4
1552 ALN2 = -(C1 - C2 + ARCL5+CSPM5) / CSPM4
1553 ARCL(M4) = ALN2
1554 GO TO 480
1555 C
1556 C NO PRISMATIC JOINTS, THREE REVOLUTE JOINTS
1557 C
1558 ARCL4 = ARCL(M4)
1559 ARCL5 = ARCL(M5)
1560 CFS = C1 * C1 + C2 * C2
1561 C3 = CFS + (ARCL5 + ARCL4) * (ARCL5 - ARCL4)
1562 TARCL5 = 2.0 * ARCL5
1563 C4 = TARCL5 * C1
1564 C5 = TARCL5 * C2
1565 IF (DABS(C1) .GT. 0.00001) GO TO 430
1566 COSDTH = C3 / (TARCL5*DSORT(CFS))
Listing of TOCALM at 16:46:02 on JUL 23, 1982 for CCid=MC88

1567 IF (DABS(COSDTH) .LE. 1.0) GO TO 450
1568 C52S = C5 * C5
1569 C6 = C4 * C4 + C52S
1570 ARG = (C4 + C3) * (C4 - C3) + C52S
1571 TRYA = TUOSTA * ARCL4 * ARCL5
1572 TRYAS = TRYA * TRYA
1573 IF (ARG .GE. TRYAS) GO TO 460
1574 IF (ARG .GE. 0.00001) GO TO 440
1575 FLK = DSQRT(CFS)
1576 GO TO 550
1577 440 TRYA = DSQRT(ARG)
1578 STANG = TRYA / ARCL4 / TARCL5
1579 ATANG = (HPI - DARSIN(STANG)) / DEGRAD
1580 IF (ITANG .EQ. 1) GO TO 460
1581 ITANG = 1
1582 C-----FREE ENDS OF DETERMINED ARCS LIE IN A VERTICAL LINE
1583 450 THMS = DATAN2(-C2,-C1) - CONFIG(J) * DARCOS(COSDTH)
1584 SINM5 = DSIN(THMS)
1585 COSM5 = DCOS(THMS)
1586 THETA(M5) = THMS
1587 GO TO 470
1588 460 SINM5 = (-C3*C5 + CONFIG(J)*C4*DSQRT(ARG)) / C6
1589 COSM5 = -(C3 + C5*SINM5) / C4
1590 THETA(M5) = DATAN2(SINM5,COSM5)
1591 470 SINM4 = -(C2 + ARCL5*SINM5) / ARCL4
1592 COSM4 = -(C1 + ARCL5*COSM5) / ARCL4
1593 THETA(M4) = DATAN2(SINM4,COSM4)
1594 480 CONTINUE
1595 C
1596 C CALCULATE RESULTS
1597 C
1598 GO TO (490, 510, 500), LBA
1599 C
1600 C ANGULAR GENERATION
1601 C
1602 490 ANGDEG = THETA(LKOUT) / DEGRAD + OUTDEG
1603 AGR(NPT) = ANGDEG * DEGRAD
1604 GO TO 570
1605 C
1606 C SLIDING LINK OUTPUT
1607 C
1608 500 SGR(NPT) = ARCL(LKOUT)
1609 GO TO 570
1610 C
1611 C FUNCTION PATH GENERATION
1612 C
1613 510 THOUT = THETA(LKOUT) + OUTRAD
1614 X = XFR
1615 Y = YFR
1616 XD = 0
1617 YD = 0
1618 X2D = 0
1619 Y2D = 0
1620 IF (LKFIN .EQ. LKR) GO TO 530
1621 C
1622 C RETRACE OUTPUT LOOP BACK TO OUTPUT LINK
1623 C
1624 DO 520 I = LKRET, LKFIN
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1625  ALINT = ARCL(I)
1626  THINT = THETA(I) + GRPI
1627  CTHI = DCOS(THINT)
1628  STHI = DSIN(THINT)
1629  XI = ALINT * CTHI
1630  YI = ALINT * STHI
1631  X = X + XI
1632  Y = Y + YI
1633  520 CONTINUE
1634  C
1635  C ADD ON CONTRIBUTION OF OUTPUT LINK
1636  C
1637  530 CTHO = DCOS(THOUT)
1638  STHO = DSIN(THOUT)
1639  XI = OUTLK * CTHO
1640  YI = OUTLK * STHO
1641  X = X + XI
1642  Y = Y + YI
1643  IF (TANG .EQ. 2) GO TO 540
1644  XGR(NPT) = X
1645  YGR(NPT) = Y
1646  GO TO 570
1647  540 R = DSQRT(X*X + Y*Y)
1648  T = 0
1649  IF (R .GT. 1.0D-12) T = (DSIGN((DARSIN(Y/R) - HPI),X) + HPI)
1650  RGR(NPT) = R
1651  TGR(NPT) = T
1652  GO TO 570
1653  C  CONSTRAINTS OF LOOP CLOSURE VIOLATED
1654  C
1655  550 KOLE = KOL + IKON(NPT) - KON
1656  DO 560 I = 1, KOLE
1657       J = KON + I - 1
1658  560 CONTINUE
1659  570 CONTINUE
1660  GO TO 590
1661  C
1662  C CHECK ON LENGTH AND ANGULAR POSITION OF EACH ARC
1663  C
1664  580 DO 580 I = 1, NLOOP
1665    LKEND = (I - 1) * MAXARC
1666    M = LOOPL(I)
1667    LKM = LKEND + M
1668    FRANG = GAM(LKM)
1669    DO 580 J = 1, M
1670       L = LKEND + J
1671       THETA(L) = (THETA(L) + FRANG) / DEGRAD
1672  580 CONTINUE
1673  590 CONTINUE
1674  IF (MOTOR .GE. 0) RETURN
1675  ARCL(1) = ARCL1
1676  ARCL(2) = ARCL2
1677  RETURN
1678  C
1679  END
1680  C
1681  C * * * * * * * * * * * * * * * * * * * * * * * * * * *}
1682  C
C --ROUTINE TO CHECK NUMERICAL DIFFERENTIATION STEP AGAINST TOLERANCE

SUBROUTINE CHECK(TLAI, TLGI, TOLER, TOLEG, TOLED, DIFAV, DIFG, 
DEGRAD, KKO, ICHECK, MRNUR, IRNUR, MGNUR, IGNUR, MOTN)

IMPLICIT REAL*8(A - H, O - Z)
DIMENSION TLAI(KKO), TLGI(KKO), TOLER(KKO), TOLEG(KKO), TOLED(KKO), 
DIFAV(KKO), DIFG(KKO), MRNUR(IRNUR), MGNUR(103)

KKN = KKO - 1
KKM = KKN - 1

DO 10 J = 1, IRNUR
  KL = MRNUR(J)
  IF (DIFAV(KL) .GT. TLA(KL) .5.0D-2) GO TO 60
  10 CONTINUE
  IF (IGNUR .EQ. 0) GO TO 30
  DO 20 J = 1, IGNUR
    KL = MGNUR(J)
    IF (DIFG(KL) .GT. TLG(KL) .5.0D-2) GO TO 60
    20 CONTINUE
    IF (MOTN .LT. 2 .OR. MOTN .GT. 4) GO TO 40
    TOLER(KL) = TLA(KL)
    TOLEG(KL) = TLG(KL) / DEGRAD
    30 CONTINUE
  DO 70 J = 1, IRNUR
    KL = MRNUR(J)
    TOLER(KL) = TLA(KL)
    70 CONTINUE
  IF (IGNUR .EQ. 0) GO TO 90
  DO 80 J = 1, IGNUR
    KL = MGNUR(J)
    TOLEG(KL) = TLG(KL)
    80 CONTINUE
    IF (MOTN .EQ. 2 .OR. MOTN .EQ. 4) GO TO 100
    TOLER(KKM) = TLA(KKM)
    TOLEG(KKM) = TLG(KKM) / DEGRAD
    90 CONTINUE
    DO 100 J = 1, MOTN
      TOLEG(KKK) = TLG(KKK) / DEGRAD
      100 CONTINUE
      IF (MOTN .EQ. 4) GO TO 110
      110 CONTINUE
      ICHECK = 0
      GO TO 120

ICHECK = 1
GO TO 120

RETURN
END

C ** *************
C --ROUTINE TO IDENTIFY IDENTICAL COMMON ARCS & THEIR ALLOWABLE DEVIATIONS

SUBROUTINE COMARC(IREP, TLA, KKL)

IMPLICIT REAL*8(A - H, O - Z)

DIMENSION IREP(KKL), MK(100), ML(10), MJ(10, 10), NC(10), TLA(KKL)

NR = 0
JL = 0
DO 20 L = 1, KKL
IF (IREP(L) EQ. 0) GO TO 20
IF (IREP(L) NE. L) GO TO 10
NR = NR + 1
ML(NR) = L
20 CONTINUE

IF (NR EQ. 0) GO 10-90
DO 40 KL = 1, NR
NC(KL) = 0
DO 30 NL = 1, A
IF (IREP(MK(NL)) NE. IREP(ML(KL))) GO TO 30
NC(KL) = NC(KL) + 1.
MJ(KL, NC(KL)) = KK(NL)
30 CONTINUE
40 CONTINUE

DO 70 KL = 1, NR
SMALL = 1.0D+03
MC = NC(KL)
DO 50 NL = 1, MC
IF (TLA(MJ(KL, NL)) LT. SMALL) SMALL = TLA(MJ(KL, NL))
50 CONTINUE
DO 60 NL = 1, MC
TLA(MJ(KL, NL)) = SMALL
60 CONTINUE
70 CONTINUE
80 RETURN

END

C --ROUTINE FOR REARRANGING ARC DEVIATIONS IN ASCENDING ORDER

SUBROUTINE ORDER(TLA, MN, M)

IMPLICIT REAL*8(A - H, O - Z)

DIMENSION TLA(M), MN(M)

DO 10 I = 1, M
M(N) = I
10 CONTINUE
DO 30 K = 2, N
DO 20 L = 2, K
J = I + 1
IF (TLA(MN(J)) .GE. TLA(MN(I))) GO TO 30
MT = MN(J)
MN(J) = MN(I)
MN(I) = MT
20 CONTINUE
30 CONTINUE

C -- ROUTINE FOR MODIFYING DEVIATIONS BY MULTIPLYING BY RATIO OF ALLOUABLE/MAXIMUM OF OUTPUT DEVIATION
C
C ROUTINE FOR MODIFYING DEVIATIONS BY MULTIPLYING BY RATIO OF ALLOUABLE/MAXIMUM OF OUTPUT DEVIATION
C
SUBROUTINE CORFAC(NDES, KKL, KKM, KKN, KKO)
C
IMPLICIT REAL*8(A - HIG - Z)

COMMON /CORR/ OUTOLX, OUTOLY, OUTOLA, OUTOLR, OUTOLT, OUTOLS,
1 PDX(37,100), PDY(37,100), PDGX(37,100), PDGY(37,100),
2 PDA(37,100), PDGA(37,100), PDR(37,100), PDT(37,100),
3 PDRG(37,100), PDRG(37,100), PDS(37,100), PDGS(37,100),
4 PDOLX(37), PDOLY(37), PDOLX(37), PDOLY(37),
5 PDGX(37), PDGY(37), PDGY(37),
6 PDORLX(37), PDORLY(37), PDORLX(37), PDORLY(37),
7 PDOLR(37), PDOLR(37), PDOLR(37),
8 PDORL(37), PDORL(37), PDORL(37),
9 DEVR(37), DEVR(37), DEVR(37),
10 DEVA(37), DEVA(37), DEVA(37),
11 DEVT(37), DEVT(37), DEVT(37),

FACTOR = DEGRAD = DATAN(1.0D+0) / 4.5D+1

DO 210 J = 1, NDES
GO TO (10, 60, 110, 160), MOTH

10 DEVX(J) = 0.0D+0
11 DEVY(J) = 0.0D+0
DO 50 I = 1, KKL
IF (TLA(I) .GT. 9.9D+2) GO TO 20
DEUX(J) = DEUX(J) + (PDX(J,I) * TLA(I)) ** 2
DEUY(J) = DEUY(J) + (PDY(J,I) * TLA(I)) ** 2
GO TO 30
20 PDX(J,I) = -1.0D+0
30 IF (TLG(I) .GT. 9.9D+2) GO TO 40
DEUX(J) = DEUX(J) + (PDGX(J,I) * TLG(I)) ** 2
DEUY(J) = DEUY(J) + (PDGY(J,I) * TLG(I)) ** 2
GO TO 50
40 PDGX(J,I) = -1.0D+0
50 CONTINUE
IF (TLA(KKM) .GT. 9.9D+2) GO TO 52
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1807 \[ \text{DEVX}(J) = \text{DEVX}(J) + (\text{PDOLX}(J) \times \text{TLA}(KKM)) \times 2 + (\text{PDGDX}(J) \times \text{TLG}(KKM)) \times 2 \]
1808 \( \text{KKN}) \times 2 \]
1809 \[ \text{DEVY}(J) = \text{DEVY}(J) + (\text{PDOLY}(J) \times \text{TLA}(KKM)) \times 2 + (\text{PDGGY}(J) \times \text{TLG}(KKM)) \times 2 \]
1810 \[ \text{GO TO 54} \]
1811 \[ \text{PDOLX}(J) = -1.0D+0 \]
1812 \[ \text{PDOLY}(J) = -1.0D+0 \]
1813 \[ \text{PDGDX}(J) = -1.0D+0 \]
1814 \[ \text{PDGGY}(J) = -1.0D+0 \]
1815 \[ \text{IF } (\text{TLA}(KKM) \geq 9.9D+2) \text{ GO TO 56} \]
1816 \[ \text{DEVX}(J) = \text{DEVX}(J) + (\text{PDORLX}(J) \times \text{TLA}(KKN)) \times 2 + (\text{PDORGX}(J) \times \text{TLG}(KKN)) \times 2 \]
1817 \[ \text{DEVY}(J) = \text{DEVY}(J) + (\text{PDORLY}(J) \times \text{TLA}(KKN)) \times 2 + (\text{PDORGY}(J) \times \text{TLG}(KKN)) \times 2 \]
1818 \[ \text{GO TO 58} \]
1819 \[ \text{PDORLX}(J) = -1.0D+0 \]
1820 \[ \text{PDORLY}(J) = -1.0D+0 \]
1821 \[ \text{PDORGX}(J) = -1.0D+0 \]
1822 \[ \text{PDORGY}(J) = -1.0D+0 \]
1823 \[ \text{IF } (\text{TLA}(KKN) > 9.9D+2) \text{ GO TO 56} \]
1824 \[ \text{DEVX}(J) = \text{DEVX}(J) + (\text{PDOLX}(J) \times \text{TLA}(KKM)) \times 2 + (\text{PDGDX}(J) \times \text{TLG}(KKM)) \times 2 \]
1825 \[ \text{DEVY}(J) = \text{DEVY}(J) + (\text{PDOLY}(J) \times \text{TLA}(KKM)) \times 2 + (\text{PDGGY}(J) \times \text{TLG}(KKM)) \times 2 \]
1826 \[ \text{GO TO 210} \]
1827 \[ \text{DO 100 } I = 1, \text{KKN} \]
1828 \[ \text{IF } (\text{TLA}(I) \geq 9.9D+2) \text{ GO TO 70} \]
1829 \[ \text{DEVX}(J) = \text{DEVX}(J) + (\text{PDA}(J,I) \times \text{TLA}(I)) \times 2 \]
1830 \[ \text{GO TO 80} \]
1831 \[ \text{PDOLX}(J) = -1.0D+0 \]
1832 \[ \text{PDOLY}(J) = -1.0D+0 \]
1833 \[ \text{PDGDX}(J) = -1.0D+0 \]
1834 \[ \text{PDGGY}(J) = -1.0D+0 \]
1835 \[ \text{GO TO 100} \]
1836 \[ \text{PDOLX}(J) = -1.0D+0 \]
1837 \[ \text{PDOLY}(J) = -1.0D+0 \]
1838 \[ \text{PDGDX}(J) = -1.0D+0 \]
1839 \[ \text{PDGGY}(J) = -1.0D+0 \]
1840 \[ \text{GO TO 100} \]
1841 \[ \text{PDOLX}(J) = -1.0D+0 \]
1842 \[ \text{PDOLY}(J) = -1.0D+0 \]
1843 \[ \text{PDGDX}(J) = -1.0D+0 \]
1844 \[ \text{PDGGY}(J) = -1.0D+0 \]
1845 \[ \text{END} \]
1846 \[ \text{END} \]
1847 \[ \text{END} \]
1848 \[ \text{END} \]
1849 \[ \text{END} \]
1850 \[ \text{END} \]
1851 \[ \text{END} \]
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1863 \[ \text{END} \]
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1872 \[ \text{END} \]
1873 \[ \text{END} \]
1874 \[ \text{END} \]
1875 \[ \text{END} \]
1876 \[ \text{END} \]
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1912 \[ \text{END} \]
1913 \[ \text{END} \]
1914 \[ \text{END} \]
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1915  PDGT(J,1) = -1.0D+0
1916  CONTINUE
1917  IF (TLA(KKM) .GE. 9.9D+2) GO TO 152
1918  DEVR(J) = DEVR(J) + (PDOLR(J)*TLA(KKM)) ** 2 + (PDORR(J)*TLG(KKM)) ** 2
1919  CONTINUE
1920  DEVT(J) = DEVT(J) + (PDOGR(J)*TLA(KKM)) ** 2 + (PDORR(J)*TLG(KKM)) ** 2
1921  CONTINUE
1922  GO TO 154
1923  PDOLR(J) = -1.0D+0
1924  PDOLR(J) = -1.0D+0
1925  PDOLR(J) = -1.0D+0
1926  PDOLR(J) = -1.0D+0
1927  IF (TLA(KKM) .GE. 9.9D+2) GO TO 156
1928  DEVR(J) = DEVR(J) + (PDORR(J)*TLA(KKM)) ** 2 + (PDGRR(J)*TLG(KKM)) ** 2
1929  CONTINUE
1930  DEVT(J) = DEVT(J) + (PDORR(J)*TLA(KKM)) ** 2 + (PDGRR(J)*TLG(KKM)) ** 2
1931  CONTINUE
1932  GO TO 158
1933  PDORR(J) = -1.0D+0
1934  PDORR(J) = -1.0D+0
1935  PDORR(J) = -1.0D+0
1936  PDORR(J) = -1.0D+0
1937  IF (TLA(KKM) .GE. 9.9D+2) GO TO 157
1938  DEVS(J) = DEVS(J) + (PDS(J,I)*TLA(I)) ** 2
1939  CONTINUE
1940  PDGRR(J) = -1.0D+0
1941  IF (TLG(I) .GT. 9.9D+2) GO TO 190
1942  DEVS(J) = DEVS(J) + (PDGS(J,I)*TLG(I)) ** 2
1943  GO TO 200
1944  CONTINUE
1945  PDGS(J,I) = -1.0D+0
1946  DO 200 I = 1, KKL
1947  IF (TLA(I) .GE. 9.9D+2) GO TO 170
1948  DEVS(J) = DEVS(J) + (PDS(J,I)*TLA(I)) ** 2
1949  GO TO 180
1950  CONTINUE
1951  PDS(J,I) = -1.0D+0
1952  IF (TLG(I) .GE. 9.9D+2) GO TO 190
1953  PDGS(J,I) = -1.0D+0
1954  CONTINUE
1955  PDGS(J,I) = -1.0D+0
1956  CONTINUE
1957  CONTINUE
1958  CONTINUE
1959  CONTINUE
1960  CONTINUE
1961  GO TO (220, 240, 260, 280), MMN
1962  CONTINUE
1963  CALL DEVMAX(DEVX, NDES, DMAX)
1964  FACTRX = OUTFOLX / DMAX
1965  CALL DEVMAX(DEVY, NDES, DMAX)
1966  FACTRY = OUTFOLY / DMAX
1967  FACTOR = FACTRX
1968  IF (FACTRY .LT. FACTRX) FACTOR = FACTRY
1969  DO 230 J = 1, NDES
1970  DEVX(J) = DEVX(J) * FACTOR
1971  DEVY(J) = DEVY(J) * FACTOR
1972  CONTINUE
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1973 C
1974 GO TO 300
1975 C
1976 240 CALL DEVMAX(DEVA, NDES, DMAX)
1977 FACTOR = OUTOLA * DEGRAD / DMAX
1978 DO 250 J = 1, NDES
1979 DEVA(J) = DEVA(J) * FACTOR / DEGRAD
1980 250 CONTINUE
1981 C
1982 GO TO 300
1983 C
1984 260 CALL DEVMAX(DEVR, NDES, DMAX)
1985 FACTRR = OUTOLR / DMAX
1986 CALL DEVMAX(DEVT, NDES, DMAX)
1987 FACTRT = OUTOLT * DEGRAD / DMAX
1988 FACTOR = FACTRR
1989 IF (FACTRT .LT. FACTRR) FACTOR = FACTRT
1990 DO 270 J = 1, NDES
1991 DEVR(J) = DEVR(J) * FACTOR
1992 DEVT(J) = DEVT(J) * FACTOR / DEGRAD
1993 270 CONTINUE
1994 C
1995 GO TO 300
1996 C
1997 280 CALL DEVMAX(DEVS, NDES, DMAX)
1998 FACTOR = OUTOLS / DMAX
1999 DO 290 J = 1, NDES
2000 DEVS(J) = DEVS(J) * FACTOR
2001 290 CONTINUE
2002 C
2003 300 DO 310 I = 1, KKO
2004 IF (TLAM GT. 9.9D+2) GO TO 310
2005 TLAM = TLAM * FACTOR
2006 IF (TLAG(I) GT. 9.9D+2) GO TO 310
2007 TLAG(I) = TLAG(I) FACTOR
2008 310 CONTINUE
2009 C
2010 RETURN
2011 END
2012 C
2013 C * * * * * * * * * * * * * * * *
2014 C
2015 C -- ROUTINE FOR IDENTIFYING MAXIMUM DEVIATION OF OUTPUT
2016 C
2017 SUBROUTINE DEVMAX(ARRAY, N, DMAX)
2018 C
2019 IMPLICIT REAL*8(A - H, O - Z)
2020 DIMENSION ARRAY(N)
2021 C
2022 DMAX = ARRAY(1)
2023 DO 10 I = 2, N
2024 IF (ARRAY(I) .GT. DMAX) DMAX = ARRAY(I)
2025 10 CONTINUE
2026 C
2027 RETURN
2028 END
2029 C
2030 C * * * * * * * * * * * * * * * *
C--ROUTINE TO ALLOCATE ARC LENGTH & ANGLE TOLERANCES & JOINT CLEARANCES

SUBROUTINE RESULT(IREP, ITERN, KKL, KKN, NLOOP, MAXARC, LORDER,
                   TLA, KKN, IGNUR, TLG, KKO, NOUTLK, NOUTLP, KLINK, ARCL,
                   GAMNA, MOTN, CLIMIT)

IMPLICIT REAL*8(A - H, O - Z)

DIMENSION IREP(KKL), ITERN(KKL), LORDER(KKN), TLA(KKN), TLG(KKO),
        CLNCE(10,10,10), ARCL(KKN), GAMNA(KKO), LTERN(105),
        ICL(10,10,10)

RADEG = 4.5D+1 / DATAN(1.0D+0)

DO 30 A = 1, NLOOP
  IF (MAXARC .EQ. 4) GO TO 20
  DO 10 JA = 1, MAXARC
    LN = (A - 1) * MAXARC + A
    IF (KLINK(LN) .NE. 0) GO TO 10
    MAXR(A) = A - 1
  60 TO 30
  10 CONTINUE
  20 MAXR(JL) = MAXARC
  30 CONTINUE

NNN = KKN

DO 40 A = 1, NLOOP
  NIM = MAXR(JL)
  DO 40 JA = 1, NIM
    JM = JA - 1
    IF (JM .EQ. 0) JM = MAXR(JL)
    CLNCE(JM, JA, JL) = -1.0D+0
    ICL(JM, JA, JL) = 1.0D+0
  40 CONTINUE

NNN = KKN

IF (MOTH .EQ. 2 .OR. MOTH .EQ. 4) NNN = KKL

DO 720 IT = 1, NNN
  IORD = LORDER(IT)
  IF (TLA(IORD) .GT. 9.99D+02) 60 70 730
  IF (IORD .EQ. KKM) 60 TO 640
  IF (IORD .EQ. KKN) GO TO 690
  CALL JSBSCR(IORD, MAXARC, NOLP, NOAR, LPI, LFI, MAXR, NLOOP)
  IF (IREP(IORD) .EQ. 0 .OR. IREP(IORD) .EQ. IORD) GO TO 50
  50 CONTINUE

CALL JSBSCR(IORD, MAXARC, LPRNM, IRNRM, LP, LF, MAXR, NLOOP)

IF (IREP(IORD) .EQ. 0 .OR. IREP(IORD) .EQ. IORD) GO TO 50
  50 CONTINUE

CALL JSBSCR(IORD, MAXARC, NOAR, NOAR, LPI, LFI, MAXR, NLOOP)

JPF = (LPRNM - 1) * MAXARC + LP
JFF = (LPRNM - 1) * MAXARC + LF
JPS = (NOAR - 1) * MAXARC + LPI
JFS = (NOAR - 1) * MAXARC + LFI

TLNCE(IRNRM, LPRNM) = TLNCE(NOAR, NOLP)

CLNCE(LP, IRNRM, LPRNM) = CLNCE(LP, NOAR, NOLP)

IF ((IREP(JPF) .EQ. IREP(JPS) .OR. IREP(JPF) .EQ. IREP(JFS)))

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2089 1 AND. IREP(JPF) NE. 0 ICL(LP,IRNUM,LPNUM) = 0
2090 CLNCE(IRNUM,LF,LPNUM) = CLNCE(NOAR,LFI,NOLP)
2091 IF ( (IREP(JFF) .EQ. IREP(JFS) .OR. IREP(JFF) .EQ. IREP(JPS)) .
2092 1 AND. IREP(JFF) NE. 0) ICL(LP,IRNUM,LPNUM) = 0
2093 GO TO 90
2094 C
2095 50 IF (CLNCE(LP,IRNUM,LPNUM) LT. 0.0D+0 .AND. CLNCE(IRNUM,LF,
2096 1 LPNUM) DT. 0.0D+0) GO TO 60
2097 IF (CLNCE(IRNUM,LF,LPNUM) LT. 0.0D+0) GO TO 70
2098 IF (CLNCE(LP,IRNUM,LPNUM) LT. 0.0D+0) GO TO 60
2099 C
2100 C  CLEARANCES AT BOTH ENDS OF ARC ALREADY DETERMINED
2101 CLNCE(IRNUM,LPNUM) = TLA(IORD)
2102 NLT = 1
2103 GO TO 90
2104 C
2105 C  CLEARANCE AT FOLLOWING JOINT ALREADY DETERMINED
2106 60 TLNCE(IRNUM,LPNUM) = TLA(IORD) / DSORT(1.25D+0)
2107 CLNCE(LP,IRNUM,LPNUM) = 0.5D+0 * TLNCE(IRNUM,LPNUM)
2108 IF (ARCL(IORD) LT. TLA(IORD)) CLNCE(LP,IRNUM,LPNUM) = TLA(IORD)
2109 NLT = 2
2110 IF (CLNCE(LP,IRNUM,LPNUM) LE. CLIMIT) GO TO 90
2111 CLNCE(LP,IRNUM,LPNUM) = CLIMIT
2112 TLNCE(IRNUM,LPNUM) = DSORT(TLA(IORD)**2 - CLIMIT**2)
2113 GO TO 90
2114 C
2115 C  CLEARANCE AT PRECEEDING JOINT ALREADY DETERMINED
2116 70 TLNCE(IRNUM,LPNUM) = TLA(IORD) / DSORT(1.25D+0)
2117 CLNCE(LP,IRNUM,LPNUM) = 0.5D+0 * TLNCE(IRNUM,LPNUM)
2118 IF (ARCL(IORD) LT. TLA(IORD)) CLNCE(LP,IRNUM,LPNUM) = TLA(IORD)
2119 NLT = 3
2120 IF (CLNCE(LP,IRNUM,LPNUM) LE. CLIMIT) GO TO 90
2121 CLNCE(LP,IRNUM,LPNUM) = CLIMIT
2122 TLNCE(IRNUM,LPNUM) = DSORT(TLA(IORD)**2 - CLIMIT**2)
2123 GO TO 90
2124 C
2125 C  CLEARANCES AT BOTH ENDS YET TO BE DETERMINED
2126 80 TLNCE(IRNUM,LPNUM) = TLA(IORD) / DSORT(1.5D+0)
2127 CLNCE(LP,IRNUM,LPNUM) = 0.5D+0 * TLNCE(IRNUM,LPNUM)
2128 IF (ARCL(IORD) LT. TLA(IORD)) CLNCE(LP,IRNUM,LPNUM) = TLA(IORD)
2129 1 / DSORT(2.0D+0)
2130 CLNCE(LP,IRNUM,LPNUM) = CLNCE(LP,IRNUM,LPNUM)
2131 NLT = 4
2132 IF (CLNCE(LP,IRNUM,LPNUM) LE. CLIMIT) GO TO 90
2133 CLNCE(LP,IRNUM,LPNUM) = CLIMIT
2134 CLNCE(LP,IRNUM,LPNUM) = CLIMIT
2135 TLNCE(IRNUM,LPNUM) = DSORT(TLA(IORD)**2 - 2.0D+0*CLIMIT**2)
2136 C
2137 C  IF LINK IS TERNARY REALLOCATE TOLERANCES AND CLEARANCES
2138 90 IF (ITERN(IORD) .EQ. 0) GO TO 720
2139 CALL TERNRY(ARCL, ITERN, IORD, LTERN, KKL, NLOOP, KXX)
2140 C
2141 DO 100 KTI = 1, KXX
2142 KORD = LTERN(KTI)
2143 CALL JSBSCR(KORD, MAXARC, NOLP, NOAR, LPT, LFT, MAXR, NLOOP)
2144 IF (TLNCE(NOAR,NOLP) .GT. 0.0D+0) GO TO 720
2145 100 CONTINUE
2146 C
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2147 DO 630 KNN = 1, KXX
2148 KORD = ITERN(KNN)
2149 CALL JSBSCR(KORD, MAXARC, NOLP, NOAR, LPT, LFT, MAXR, NLOOP)
2150 NJP = (NOLP - 1) * MAXARC + LPT
2151 NJP = (LPNUM - 1) * MAXARC + LP
2152 NJF = (NOLP - 1) * MAXARC + LFT
2153 NJF = (LPNUM - 1) * MAXARC + LF
2154 C
2155 IF (((IREP(MJP) .EQ. IREP(NJP)) .AND. IREP(MJP) .NE. 0) .OR. (2156 IF ((IREP(MJF) .EQ. IREP(NJF)) .AND. IREP(MJF) .NE. 0) .OR. (2157 IF ((IREP(MJP) .EQ. IREP(NJF)) .AND. IREP(MJP) .NE. 0) .OR. (2158 IF ((IREP(MJP) .EQ. IREP(NJF)) .AND. IREP(MJF) .NE. 0) .OR. (2159 IF ((IREP(MJP) .EQ. IREP(NJF)) .AND. IREP(MJF) .NE. 0) .OR. (2160 IF ((IREP(MJP) .EQ. IREP(NJF)) .AND. IREP(MJF) .NE. 0) .OR. (2161 IF ((IREP(MJP) .EQ. IREP(NJF)) .AND. IREP(MJF) .NE. 0) .OR. (2162 IF ((IREP(MJP) .EQ. IREP(NJF)) .AND. IREP(MJF) .NE. 0) .OR. (2163 IF ((IREP(MJP) .EQ. IREP(NJF)) .AND. IREP(MJF) .NE. 0) .OR. (2164 IF ((IREP(MJP) .EQ. IREP(NJF)) .AND. IREP(MJF) .NE. 0) .OR. (2165 IF ((IREP(MJP) .EQ. IREP(NJF)) .AND. IREP(MJF) .NE. 0) .OR. (2166 C .. PRECEEDING JOINTS OF BOTH ARCS COMMON
2167 110 IF (ITERN(NJP) .EQ. ITERN(KORD)) GO TO 140
2168 IF (IREP(NJP) .EQ. 0) GO TO 120
2169 IF (ITERN(IREP(NJP)) .EQ. ITERN(KORD)) GO TO 140
2170 120 IF (ITERN(NJP) .EQ. 0) GO TO 130
2171 IF (ITERN(IREP(NJP)) .EQ. ITERN(KORD)) GO TO 140
2172 130 CLNCE(LPT,NOAR,NOLP) = CLNCE(LP,IRNUM,LPNUM)
2173 140 IF (ITERN(KORD) .NE. KORD) ICL(LP,NOAR,NOLP) = 0
2174 IF (ITERN(IORD) .NE. IORD) ICL(LP,IRNUM,LPNUM) = 0
2175 CLENG = 0.5D+0 * TLA(NJF) / DSQRT(1.25D+0)
2176 IF (KORD .LT. IORD) GO TO 150
2177 TLANG(NOAR,NOLP) = TLG(KORD) / DSQRT(1.5D+0)
2178 CLANG = 0.5D+0 * ARCL(IORD) * TLANG(NOAR,NOLP)
2179 GO TO 160
2180 150 TLANG(IRNUM,LPNUM) = TLG(IORD) / DSQRT(1.5D+0)
2181 CLANG = 0.5D+0 * ARCL(IORD) * TLANG(IRNUM,LPNUM)
2182 160 IF (CLANG .GT. CLNCE(IRNUM,LF,LPNUM)) GO TO 210
2183 IF (CLANG .GT. CLNCE(NOAR,LFT,NOLP) .GT. 0.0D+0)) GO TO 170
2184 CLANG = 0.5D+0 * TLG(KORD) / DSQRT(1.25D+0)
2185 CLING = CLANG * ARCL(IORD) / ARCL(IORD)
2186 IF (CLING .LT. CLANG) GO TO 170
2187 CLNCE(IRNUM,LF,LPNUM) = CLANG
2188 IF (CLING .LT. CLENG .AND. CLING .LT. CLIMIT) CLNCE(NOAR,LFT,2189 1 NOLP) = CLING
2190 GO TO 180
2191 170 CLANG = CLANG * DSQRT(1.2D+0)
2192 IF (KORD .GT. IORD) TLANG(NOAR,NOLP) = 2.0D+0 * CLANG / ARCL(IORD)
2193 1 IORD
2194 IF (IORD .GT. KORD) TLANG(IRNUM,LPNUM) = 2.0D+0 * CLANG / ARCL(IORD)
2195 1 IORD
2196 CLNCE(IRNUM,LF,LPNUM) = CLANG
2197 180 GO TO (630, 630, 190, 200), MLT
2198 190 TLNC(E(IRNUM,LPNUM) = TLA(IORD)
2199 GO TO 630
2200 200 TLNC(E(IRNUM,LPNUM) = TLA(IORD) / DSQRT(1.25D+0)
2201 CLNCE(LP,IRNUM,LPNUM) = 0.5D+0 * TLNC(E(IRNUM,LPNUM)
2202 CLNCE(LP,NOAR,NOLP) = CLNCE(LP,IRNUM,LPNUM)
2203 IF (CLNCE(LP,IRNUM,LPNUM) .LE. CLIMIT) GO TO 630
2204 CLNCE(LP,IRNUM,LPNUM) = CLIMIT
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2205 \text{CLNCE}(\text{LPT}, \text{NOAR}, \text{NOLP}) = \text{CLIMIT}

2206 \text{TLNCE}(\text{IRNUM}, \text{LPNUM}) = \text{DSORT}(\text{TLA}(\text{IORD})**2 - \text{CLIMIT}**2)

2207 \text{GO TO} 630

2208 210 IF (CLNCE(\text{NOAR}, \text{LFT}, \text{NOLP}) \gt 0.0D+0) \text{GO TO} 220

2209 \text{CLING} = \text{CLANG} * \text{DSORT}(1.2D+0) * \text{ARCL}(\text{KORD}) / \text{ARCL}(\text{IORD})

2210 \text{CLUNG} = 0.5D+0 * \text{TLA}(\text{KORD}) / \text{DSORT}(1.25D+0)

2211 IF (CLUNG \gt \text{CLING}) \text{GO TO} 230

2212 220 IF (\text{KORD} \gt \text{IORD}) \text{TLANG}(\text{NOAR}, \text{NOLP}) = \text{TLG}(\text{KORD})

2213 IF (\text{IORD} \gt \text{KORD}) \text{TLANG}(\text{IRNUM}, \text{LPNUM}) = \text{TLG}(\text{IORD})

2214 \text{GO TO} 630

2215 230 IF (\text{CLING} \gt \text{CLENG} \text{AND} \text{CLING} \lt \text{CLIMIT}) \text{CLNCE}(\text{NOAR}, \text{LFT}, \text{NOLP}) = \text{CLING}

2216 1 \text{NOLP} = \text{CLING}

2217 IF (\text{KORD} \gt \text{IORD}) \text{TLANG}(\text{NOAR}, \text{NOLP}) = 2.0D+0 * \text{CLING} / \text{ARCL}(\text{KORD})

2218 1 \text{KORD} = \text{CLING}

2219 IF (\text{IORD} \gt \text{KORD}) \text{TLANG}(\text{IRNUM}, \text{LPNUM}) = 2.0D+0 * \text{CLING} / \text{ARCL}(\text{KORD})

2220 \text{GO TO} 630

2221

2222 C

2223 .. FOLLOWING JOINTS OF BOTH ARCS COMMON

2224 240 IF (\text{INTERN}(\text{KORD}) \text{EQ} \text{INTERN}(\text{NJF})) \text{GO TO} 270

2225 IF (\text{IREP}(\text{KORD}) \text{EQ} 0) \text{GO TO} 250

2226 IF (\text{INTERN}(\text{IREP}(\text{KORD})) \text{EQ} \text{INTERN}(\text{NJF})) \text{GO TO} 270

2227 250 IF (\text{IREP}(\text{NJF}) \text{EQ} 0) \text{GO TO} 260

2228 IF (\text{INTERN}(\text{KORD}) \text{EQ} \text{INTERN}(\text{IREP}(\text{NJF}))) \text{GO TO} 270

2229 260 \text{CLNCE}(\text{NOAR}, \text{LFT}, \text{NOLP}) = \text{CLNCE}(\text{IRNUM}, \text{LFT}, \text{LPNUM})

2230 270 IF (\text{INTERN}(\text{KORD}) \text{NE} \text{INTERN}(\text{NJF}) \text{NE} \text{INTERN}(\text{IREP}(\text{NJF}))) \text{GO TO} 270

2231 \text{CLENG} = 0.5D+0 * \text{TLA}(\text{NJF}) / \text{DSORT}(1.25D+0)

2232 \text{IF} (\text{KORD} \gt \text{KORD}) \text{GO TO} 280

2233 \text{IF} (\text{IORD} \gt \text{IORD}) \text{GO TO} 280

2234 \text{IF} (\text{CLANG} \lt \text{CLNCE}(\text{LPT}, \text{NOAR}, \text{NOLP}) \text{AND} \text{CLMNG} \lt \text{CLLIMIT}) \text{CLNCE}(\text{NOAR}, \text{LFT}, \text{NOLP}) = \text{CLNCE}(\text{IRNUM}, \text{LFT}, \text{LPNUM})

2235 \text{GO TO} 290

2236 \text{GO TO} 290

2237 280 \text{TLANG}(\text{IRNUM}, \text{LPNUM}) = \text{TLG}(\text{IORD}) / \text{DSORT}(1.5D+0)

2238 \text{CLANG} = 0.5D+0 * \text{ARCL}(\text{IORD}) * \text{TLANG}(\text{NOAR}, \text{NOLP})

2239 \text{GO TO} 290

2240 \text{GO TO} 290

2241 \text{CLUNCE}(\text{NOAR}, \text{LFT}, \text{NOLP}) = \text{CLNCE}(\text{IRNUM}, \text{LFT}, \text{LPNUM})

2242 \text{CLANG} = 0.5D+0 * \text{ARCL}(\text{IORD}) * \text{TLANG}(\text{NOAR}, \text{NOLP})

2243 \text{GO TO} 300

2244 \text{IF} (\text{CLING} \lt \text{CLENG} \text{AND} \text{CLING} \lt \text{CLLIMIT}) \text{CLNCE}(\text{LPT}, \text{NOAR}, \text{NOLP}) = \text{CLANG}

2245 \text{GO TO} 310

2246 \text{GO TO} 310

2247 \text{GO TO} 310

2248 300 \text{CLANG} = \text{CLANG} * \text{DSORT}(1.2D+0)

2249 \text{GO TO} 310

2250 \text{IF} (\text{KORD} \gt \text{IORD}) \text{TLANG}(\text{NOAR}, \text{NOLP}) = 2.0D+0 * \text{CLANG} / \text{ARCL}(\text{IORD})

2251 \text{IF} (\text{IORD} \gt \text{KORD}) \text{TLANG}(\text{IRNUM}, \text{LPNUM}) = 2.0D+0 * \text{CLANG} / \text{ARCL}(\text{IORD})

2252 \text{GO TO} 320

2253 \text{CLNCE}(\text{LP}, \text{IRNUM}, \text{LPNUM}) = \text{CLANG}

2254 \text{GO TO} 320

2255 \text{GO TO} 320

2256 \text{GO TO} 630

2257 \text{GO TO} 630

2258 \text{GO TO} 630

2259 \text{TLNCE}(\text{IRNUM}, \text{LPNUM}) = \text{TLA}(\text{IORD}) / \text{DSORT}(1.25D+0)

2260 \text{IF} (\text{CLNCE}(\text{IRNUM}, \text{LFT}, \text{LPNUM}) \IE \text{CLLIMIT}) \text{GO TO} 630

2261 \text{CLNCE}(\text{IRNUM}, \text{LFT}, \text{LPNUM}) = \text{CLLIMIT}

2262 \text{CLNCE}(\text{NOAR}, \text{LFT}, \text{NOLP}) = \text{CLLIMIT}
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2263 \( TLNCE(IRNUM,LPNUM) = DSORT(TLA(IORD)**2 - CLIMIT**2) \)
2264 \( \text{GO TO 630} \)
2265 340 IF (CLNCE(LPT,NOAR,NOLP) .GT. 0.0D+0) GO TO 350
2266 CLING = CLANG * DSORT(1.25D+0) / ARCL(KORD) / ARCL(IORD)
2267 CLUNG = 0.5D+0 * TLA(KORD) / DSORT(1.25D+0)
2268 IF (CLUNG .GT. CLING) GO TO 360
2269 350 IF (KORD .GT. IORD) TLANG(NOAR,NOLP) = TLA(KORD)
2270 IF (IORD .GT. KORD) TLANG(IRNUM,LPNUM) = TLA(IORD)
2271 \( \text{GO TO 630} \)
2272 360 IF (CLING .LT. CLENG AND CLING .LT. CLIMIT) CLNCE(LPT,NOAR,
2273 1 NOLP) = CLING
2274 IF (KORD .GT. IORD) TLANG(NOAR,NOLP) = 2.0D+0 * CLING / ARCL( 
2275 1 KORD)
2276 IF (IORD .GT. KORD) TLANG(IRNUM,LPNUM) = 2.0D+0 * CLING / 
2277 1 ARCL(KORD)
2278 \( \text{GO TO 630} \)
2279 C
2280 C .. PRECEEDING JOINT OF CURRENT ARC & FOLLOWING OF OTHER COMMON
2281 370 IF (ITERN(KORD) .EQ. ITERN(NJF)) GO TO 400
2282 IF (IREP(KORD) .EQ. 0) GO TO 380
2283 IF (ITERN(IREP(KORD)) .EQ. ITERN(NJF)) GO TO 400
2284 380 IF (ITERN(KORD) .EQ. ITERN(IREP(NJF))) GO TO 400
2285 390 CLNCE(NOAR,LFT,NOLP) = CLNCE(LP,IRNUM,LPNUM)
2286 400 IF (ITERN(KORD) .NE. KORD) ICL(NOAR,LFT,NOLP) = 0
2287 IF (ITERN(IORD) .NE. IORD) ICL(LP,IRNUM,LPNUM) = 0
2288 CLENG = 0.5D+0 * TLA(NJP) / DSORT(1.25D+0)
2289 IF (KORD .LT. IORD) GO TO 410
2290 TLANG(NOAR,NOLP) = TLA(KORD) / DSORT(1.5D+0)
2291 CLANG = 0.5D+0 * ARCL(IORD) * TLANG(NOAR,NOLP)
2292 \( \text{GO TO 420} \)
2293 410 TLANG(IRNUM,LPNUM) = TLA(IORD) / DSORT(1.5D+0)
2294 CLANG = 0.5D+0 + ARCL(IORD) + TLANG(IRNUM,LPNUM)
2295 \( \text{GO TO 420} \)
2296 420 IF (CLANG .GT. CLNCE(IRNUM,LF,LPNUM)) GO TO 470
2297 IF (CLNCE(LPT,NOAR,NOLP) .GT. 0.0D+0) GO TO 430
2298 CLUN = 0.5D+0 * TLA(KORD) / DSORT(1.25D+0)
2299 CLANG = CLANG * ARCL(KORD) / ARCL(IORD)
2300 IF (CLING .LT. CLENG AND CLING .LT. CLIMIT) CLNCE(LPT,NOAR,
2301 1 NOLP) = CLING
2302 \( \text{GO TO 440} \)
2303 430 CLANG = CLANG * DSORT(1.2D+0)
2304 IF (KORD .GT. IORD) TLANG(NOAR,NOLP) = 2.0D+0 * CLANG / ARCL( 
2305 1 IORD)
2306 IF (IORD .GT. KORD) TLANG(IRNUM,LPNUM) = 2.0D+0 + CLANG / 
2307 1 ARCL(IORD)
2308 \( \text{GO TO 440} \)
2309 440 \( \text{TLNCE(IRNUM,LPNUM) = TLA(IORD) / DSORT(1.25D+0}) \)
2310 CLNCE(LP,IRNUM,LPNUM) = 0.5D+0 + TLNCE(IRNUM,LPNUM)
2311 CLNCE(NOAR,LFT,NOLP) = CLNCE(LP,IRNUM,LPNUM)
2312 IF (CLNCE(LP,IRNUM,LPNUM) .LE. CLIMIT) GO TO 630
2313 CLNCE(LP,IRNUM,LPNUM) = CLIMIT
2314 \( \text{GO TO 630} \)
2315 450 TLNCE(IRNUM,LPNUM) = DSORT(TLA(IORD)**2 - CLIMIT**2)
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2321 GO TO 630
2322 470 IF (CLNECE(LPT,NOAR,NOLP) .GT. 0.D+0) GO TO 480
2323 CLING = CLANG * DSORT(1.2D+0) * ARCL(KORD) / ARCL(IORD)
2324 CLUNG = 0.5D+0 * TLA(KORD) / DSORT(1.25D+0)
2325 IF (CLUN .GT. CLING) GO TO 490
2326 480 IF (KORD .GT. IORD) TLANG(NOAR,NOLP) = TLA(KORD)
2327 IF (IORD .GT. KORD) TLANG(IRNUM,LPNUM) = TLA(IORD)
2328 GO TO 630
2329 490 IF (CLING .LT. CLANG AND. CLING .LT. CLIMIT) CLNCE(LPT,NOAR,
2330 1 NOLP) = CLING
2331 IF (KORD .GT. IORD) TLANG(NOAR,NOLP) = 2.0D+0 * CLING / ARCL(
2332 1 KORD)
2333 IF (IORD .GT. KORD) TLANG(IRNUM,LPNUM) = 2.0D+0 * CLING / ARCL(IORD)
2334 GO TO 630
2335 500 IF (ITERN(NJP) NE. ITERN(KORD)) GO TO 530
2336 IF (TREP(NJP) EQ. 0) GO TO 510
2337 IF (ITERN(IREP(NJP)) EQ. ITERN(KORD)) GO TO 530
2338 510 IF (IREP(KORD) EQ. 0) GO TO 520
2339 IF (ITERN(NJP) EQ. ITERN(IREP(KORD))) GO TO 530
2340 CLNCE(LPT,NOAR,NOLP) = CLNCE(IRNUM,LF,LPNUM)
2341 520 IF (ITERN(KORD) .NE. KORD) ICL(LPT,NOAR,NOLP) = 0
2342 IF (ITERN(IORD) .NE. IORD) ICL(IRNUM,LF,LPNUM) = 0
2343 CLENG = 0.5D+0 * TLA(NJF) / DSORIT(I. 25D+0)
2344 IF (KORD LT. IORD) GO TO 540
2345 TLANG(NOAR,NOLP) = TLA(KORD) / DSORT(l.5D+0)
2346 CLANG = 0.5D+0 * ARCL(IORD) * TLANG(NOAR,NOLP)
2347 GO TO 550
2348 530 IF (CLANG GT. CLNCE(LP,IRNUM,LPNUM)) GO TO 600
2349 IF (CLNECE(NDAR,LPTINOLP) GT. 0.0D+0) GO TO 560
2350 CLUNG = 0.5D+0 * TLA(KORD) / DSORT(1.25D+0)
2351 CLING = CLANG / ARCL(IORD)
2352 GO TO 550
2353 540 TLANG(IRNUM,LPNUM) = TLA(IORD) / DSORT(1.5D+0)
2354 CLANG = 0.5D+0 * ARCL(IORD) * TLANG(IRNUM,LPNUM)
2355 IF (CLANG .GT. CLNECE(LP,IRNUM,LPNUM)) GO TO 600
2356 IF (CLNECE(NOAR,LFT,NOLP) .GT. 0.0D+0) GO TO 560
2357 CLANG = 0.5D+0 * TLA(KORD) / DSORT(1.25D+0)
2358 CLING = CLANG / ARCL(KORD) / ARCL(IORD)
2359 IF (CLING .GT. CLUNG) GO TO 560
2360 CLNCE(LP,IRNUM,LPNUM) = CLANG
2361 IF (CLING .LT. CLANG AND. CLING .LT. CLIMIT) CLNCE(NOAR,LFT,
2362 1 LPNUM) = CLING
2363 GO TO 570
2364 560 CLANG = CLANG * DSORT(1.2D+0)
2365 IF (KORD .GT. IORD) TLANG(NOAR,NOLP) = 2.0D+0 * CLANG / ARCL(
2366 1 IORD)
2367 IF (IORD .GT. KORD) TLANG(IRNUM,LPNUM) = 2.0D+0 * CLANG / ARCL(IORD)
2368 CLNCE(LP,IRNUM,LPNUM) = CLANG
2369 GO TO 570
2370 570 GO TO (630, 630, 580, 590), NLT
2371 580 TLNCE(IRNUM,LPNUM) = TLA(IORD)
2372 GO TO 630
2373 590 TLNCE(IRNUM,LPNUM) = TLA(IORD) / DSORT(1.25D+0)
2374 CLNCE(IRNUM,LF,LPNUM) = 0.5D+0 * TLNCE(IRNUM,LPNUM)
2375 IF (CLNCE(IRNUM,LF,LPNUM) .LE. CLIMIT) GO TO 630
2376 CLNCE(IRNUM,LF,LPNUM) = CLIMIT
2377 CLNCE(LP,NOAR,NOLP) = CLIMIT
2378 TLNCE(IRNUM,LPNUM) = DSORT(TLA(IORD))**2 - CLIMIT**2)
2379 GO TO 630
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2379 600 IF (CLNCE(NOAR,LFT,NOLP) .GT. 0.0D+0) GO TO 610
2380 CLING = CLANG * DSORT(1.2D+0) * ARCL(KORD) / ARCL(IORD)
2381 CLUNG = 0.5D+0 * TLA(KORD) / DSORT(1.25D+0)
2382 IF (CLUNG .GT. CLING) GO TO 620
2383 610 IF (KORD .GT. IORD) TLANG(NOAR,NOLP) = TLG(KORD)
2384 IF (IORD .GT. KORD) TLANG(IRNUM,LPNUM) = TLG(IORD)
2385 GO TO 630
2386 620 IF (CLING LT. CLNCE AND. CLING LT. CLIMIT) CLNCE(NOAR,LFT,
2387 1 NOLP) = CLING
2388 IF (KORD GT. IORD) TLANG(NOAR, NOLP) = 2.0D+0 * CLING / ARCL(
2389 1 KORD)
2390 IF (IORD GT. KORD) TLANG(IRNUM, LPNUM) = 2.0D+0 * CLING / ARCL(KORD)
2391 CONTINUE
2392 C
2393 630 CONTINUE
2394 C
2395 GO TO 720
2396 C
2397 C . . OUTPUT ARC
2398 640 TLNCEO = TLA(IORD) / DSORT(1.25D+0)
2399 CLNCEO = 0.5D+0 * TLNCEO
2400 TLANG = TLG(IORD) / DSORT(1.25D+0)
2401 NAUT = (NOUTLP - 1) * MAXARC + IABS(NOUTLK)
2402 CLANG = 0.5D+0 * TLANG * ARCL(NAUT)
2403 IF (NOUTLK .LT. 0) GO TO 670
2404 NNL = NOUTLK - 1
2405 IF (CLANG .GT. CLNCEO) GO TO 650
2406 TLNCEO = TLA(IORD)
2407 IF (CLANG .GT. CLNCEO) GO TO 660
2408 CLNCEO(NNL,NOUTLK,NOUTLP) = CLANG
2409 CLNCEO(NNL,NOUTLK,NOUTLP) = CLANG
2410 IF (CLANG LE. CLIMIT) GO TO 720
2411 TLANG = DSORT(TLG(IORD)**2 - (CLIMIT/ARCL(NAUT))**2)
2412 GO TO 720
2413 650 IF (CLNCEO .GT. CLNCEO(NNL,NOUTLK,NOUTLP) .AND. CLNCEO(NNL,NOUTLK,
2414 1 NOUTLP)) .GT. 0.0D+0) GO TO 660
2415 TLANG = TLG(IORD)
2416 CLNCEO(NNL,NOUTLK,NOUTLP) = CLNCEO
2417 IF (CLNCEO .GT. CLNCEO(NNL,NOUTLK,NOUTLP) .AND. CLNCEO(NNL,NOUTLK,
2418 1 NOUTLP)) .GT. 0.0D+0) GO TO 660
2419 TLNCEO = DSORT(TLA(IORD)**2 - CLIMIT**2)
2420 GO TO 720
2421 660 TLNCEO = TLA(IORD)
2422 TLANG = TLG(IORD)
2423 GO TO 720
2424 C
2425 670 NOUTLK = -NOUTLK
2426 NNL = NOUTLK + 1
2427 IF (CLANG .GT. CLNCEO) GO TO 680
2428 TLNCEO = TLA(IORD)
2429 IF (CLANG .GT. CLNCEO(NOUTLK,NNL,NOUTLP) .AND. CLNCEO(NOUTLK,NNL,
2430 1 NOUTLP)) .GT. 0.0D+0) GO TO 660
2431 CLNCEO(NOUTLK,NNL,NOUTLP) = CLANG
2432 IF (CLANG .LE. CLIMIT) GO TO 720
2433 CLNCEO(NOUTLK,NNL,NOUTLP) = CLANG
2434 TLANG = DSORT(TLG(IORD)**2 - (CLIMIT/ARCL(NAUT))**2)
2435 GO TO 720
190

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2437  680  IF (CLNCEO .GT. CLNCE(NOUTLK,NNL,NOUTLP)) .AND. CLNCE(NOUTLK,NNL,
2438     NOUTLP) .GT. 0.0D+0) GO TO 660
2439       TLANGO = TLG(IORD)
2440       CLNCE(NOUTLK,NNL,NOUTLP) = CLNCEO
2441       IF (CLNCEO .LE. CLIMIT) GO TO 720
2442       CLNCE(NOUTLK,NNL,NOUTLP) = CLIMIT
2443       TLNCEO = DSQRT(TLA(IORD)**2 - CLIMIT**2)
2444       GO TO 720
2445
2446  690  IF (ARCL(IORD) .LT. 0.1D-3) GO TO 720
2447       C

2448       C .. ORIGIN ARC

2449       TLNCEG = TLA(IORD) / DSQRT(1.25D+0)
2450       NJI = MAXR(I)
2451       CLNCEG = 0.5D+0 * TLNCEG
2452       TLANGG = TLG(IORD) / DSQRT(1.25D+0)
2453       CLANG = 0.5D+0 * TLANGG * ARCL(IORD)
2454       IF (CLANG .GT. CLNCEG) GO TO 700
2455       TLNCEG = TLA(IORD)
2456       IF (ARCL(IORD) .LT. CLNCEG(NJI,1,1)) .AND. CLNCE(NJI,1,1) .GT. 0.0D+0)
2457       1    GO TO 710
2458       CLNCE(NJI,1,1) = CLNCEG
2459       IF (CLNCEG .LE. CLIMIT) GO TO 720
2460       CLNCEG = CLIMIT
2461       TLANGG = DSQRT(TLA(IORD)**2 - (CLIMIT/ARCL(IORD))**2)
2462       GO TO 720
2463       700  IF (CLNCEG .GT. CLNCE(NJI,1,1)) .AND. CLNCE(NJI,1,1) .GT. 0.0D+0)
2464       1    GO TO 710
2465       CLNCE(NJI,1,1) = CLNCEG
2466       TLANGG = TLG(IORD)
2467       IF (CLNCEG .LE. CLIMIT) GO TO 720
2468       CLNCEG = CLIMIT
2469       TLNCEG = DSQRT(TLA(IORD)**2 - CLIMIT**2)
2470       GO TO 720
2471       710  TLNCEG = TLA(IORD)
2472       TLANGG = TLG(IORD)
2473       C
2474       C

2475       720  CONTINUE

2476       C

2477       C .. OUTPUT ARC ANGLE

2478       730  IF (MOTN .NE. 2) GO TO 760
2479       TLANGO = TLG(KKM) / DSQRT(1.25D+0)
2480       NAUT = (NOUTLP - 1) * MAXARC + IABS(NOUTLK)
2481       CLANG = 0.5D+0 * TLANGO * ARCL(NAUT)
2482       IF (NOUTLK .LT. 0) GO TO 750
2483       NNL = NOUTLK - 1
2484       IF (CLANG .LT. 0) GO TO 740
2485       CLNCE(NNL,NOUTLK,NOUTLP) = CLANG
2486       GO TO 760
2487       740  TLANGO = TLG(KKM)
2488       GO TO 760
2489       750  NOUTLK = -NOUTLK
2490       NNL = NOUTLK + 1
2491       IF (CLANG .LT. CLNCE(NNL,NOUTLK,NOUTLP)) GO TO 740
2492       CLNCE(NOUTLK,NNL,NOUTLP) = CLANG
2493       C
2494       C .. REF POSITION OF INPUT
Listing of TOCALM at 16:46:02 on JUL 23, 1982 for CCid=MB8

2495 760 TLANGC = TLG(KKO) / DSORT(1.25D+0)
2496 MNJ = MAXR(1)
2497 MNI = MNJ - 1
2498 CLANG = 0.5D+0 * TLANGC * ARCL(MNJ)
2499 IF (CLNCE(MNI,MNJ,1) .LT. CLANG .OR. ARCL(MNJ) .LT. TLA(MNJ))
2500 1 GO TO 770
2501 CLNCE(MNI,MNJ,1) = CLANG
2502 GO TO 780
2503 770 TLANGC = TLG(KKO)
2504 C
2505 C.. PRINT OUT RESULTS
2506 780 WRITE (6,860)
2507 DO 790 ILP = 1, NLOOP
2508 NIM = MAXR(ILP)
2509 DO 790 IAR = 1, NIM
2510 IJK = (ILP - 1) * MAXARC + IAR
2511 IF (TLA(IJK) .GT. 8.0D+2 .OR. ARCL(IJK) .LT. TLA(IJK) .OR. (1
2512 IREP(IJK) .NE. 0 .AND. IREP(IJK) .NE. IJK)) GO TO 790
2513 WRITE (6,870) IAR, ILP, ARCL(IJK), CLNCE(IAR,ILP)
2514 790 CONTINUE
2515 IF (IGNUR EQ. 0) GO TO 810
2516 WRITE (6,880)
2517 DO 800 ILP = 1, NLOOP
2518 NIM = MAXR(ILP)
2519 DO 800 IAR = 1, NIM
2520 IJK = (ILP - 1) * MAXARC + IAR
2521 IF (ITERN(IJK) .EQ. 0 .OR. ITERN(IJK) .EQ. IJK) GO TO 800
2522 IF (TLG(IJK) .GT. 8.0D+2) GO TO 800
2523 TLANG(IAR,ILP) = TLANG(IAR,ILP) * RADEG
2524 WRITE (6,870) TAR, ILP, GAMA(IJK), TLANG(IAR,ILP)
2525 800 CONTINUE
2526 810 WRITE (6,890)
2527 DO 820 ILP = 1, NLOOP
2528 NIM = MAXR(ILP)
2529 DO 820 IAR = 1, NIM
2530 JAR = IAR + 1
2531 IF (IAR .EQ. MAXR(ILP)) JAR = 1
2532 IF (CLNCE(IAR,JAR,ILP) .LT. 0.0D+0) GO TO 820
2533 IF (ICL(IAR,JAR,ILP) .EQ. 0) GO TO 820
2534 WRITE (6,900) TAR, JAR, ILP, CLNCE(IAR,JAR,ILP)
2535 820 CONTINUE
2536 IF (MOTH .EQ. 4) GO TO 850
2537 IF ((MOTH .EQ. 1 .OR. MOTH .EQ. 3) .AND. ARCL(KKM) .LT. 0.1D-3)
2538 1 GO TO 840
2539 WRITE (6,910)
2540 TLANGO = TLANGO * RADEG
2541 IF (MOTH .EQ. 2) GO TO 830
2542 WRITE (6,920) ARCL(KKM), TLNCE0, GAMA(KKM), TLANGO
2543 GO TO 840
2544 830 WRITE (6,930) GAMA(KKM), TLANGO
2545 840 IF (MOTH .EQ. 2 .OR. ARCL(KKM) .LT. 0.1D-3) GO TO 850
2546 TLANGG = TLANGG * RADEG
2547 WRITE (6,940) ARCL(KKM), TLNCEG, GAMA(KKM), TLANGG
2548 850 TLANGC = TLANGC * RADEG
2549 WRITE (6,950) GAMA(KKO), TLANGC
2550 C
2551 RETURN
2552 C
Listing of TOCALM at 16:46:02 on JUL 23, 1982 for CCid=MCB8

2553 860 FORMAT (/5X, 'TOLERANCES ON ARC LENGTHS :-\/////10X, 'ARC NUMBER',
2554 1 5X, 'LOOP NUMBER', 5X, 'ARC LENGTH', 5X, 'TOLERANCE')
2555 870 FORMAT (/14X, I2, 13X, I2, 10X, F8.3, 6X, E10.4)
2556 880 FORMAT (/5X, 5X, 'TOLERANCES ON ARC ANGLES :-\/////10X, 'ARC NUMBER'
2557 1 5X, 'LOOP NUMBER', 5X, 'ANGLE MAG.', 5X, 'TOLERANCE'/41X, '(DE
2558 2GREES)', 6X, '(DEGREES)')
2559 890 FORMAT (/5X, 5X, 'CLEARANCES IN JOINTS :-\/////10X, 'PRECEEDING',
2560 1 5X, 'FOLLOWING', 6X, 'LOOP NUMBER', 5X, 'CLEARANCE'/10X, 'A
2561 2RC NUMBER', 5X, 'ARC NUMBER')
2562 900 FORMAT (/14X, 12, 13X, 12, 10X, 6XI E10.4)
2563 910 FORMAT (////5X, 'TOLERANCES ON ARC ANGL
2564 920 FORMAT (5X, 'ARC LENGTH =', F8.3, 5X, 'TOLERANCE ON ARC LENG
2565 930 FORMAT (5X, 'ARC ANGLE =', F8.3, 5X, 'TOLERANCE ON ARC ANG
2566 940 FORMAT (5X, 'ORIGIN ARC : -'/)
2567 950 FORMAT (5X, 'INPUT REFERENCE POSITION :-\/////5X, 'REFERENCE ANGL
2568 960 FORMAT (5X, 'REFERENCE ANGLE =', F8.3, 5X, 'TOLERANCE ON ARC ANG
2569 970 IF (NR #= 1) GO TO 10
2571 980 IF (NR #= JAX(NL)) GO TO 20
2572 10 IF (NR #= JAX(NL)) GO TO 20
2573 11 IF (NR #= JAX(NL)) GO TO 20
2574 12 IF (NR #= JAX(NL)) GO TO 20
2575 13 IF (NR #= JAX(NL)) GO TO 20
2576 C
2577 END
2578 C
2579 C
2580 C
2581 C
2582 C
2583 C
2584 C
2585 C
2586 C
2587 C
2588 C
2589 C
2590 IF (NR .NE. 1) GO TO 10
2591 LP = JAX(NL)
2592 LF = 2
2593 GO TO 30
2594 C
2595 C
2596 C
2597 C
2598 C
2599 C
2600 C
2601 C
2602 C
2603 C
2604 C
2605 C
2606 C
2607 C
2608 C
2609 C
2610 C

END
DIMENSION ARCL(KKL), LT(NLP), ITERN(KKL)

DO 10 I = 1, NLP
   LT(I) = 0
10 CONTINUE

KX = 0
DO 20 J = 1, KKL
   IF (J .EQ. MT) GO TO 20
   IF (ITERN(J) .NE. ITERN(MT)) GO TO 20
   IF (ARCL(J) .LT. 1.0D-3) GO TO 20
   KX = KX + 1
20   LT(KX) = J
20 CONTINUE

RETURN
END
APPENDIX IB

INPUT DATA FOR PROGRAM TOCALM
INPUT FORMAT

The input data is read from computer device 5. The first line in the data set contains the title which is printed at the top of the output. The length allowed is 72 characters.

The remaining data is read in using NAMELIST, which is a specification statement used in conjunction with the READ (n, x) and WRITE (m, x) statements. It provides for reading and writing data without including the list specification in the READ and WRITE statements. The NAMELIST statement declares a name x to refer to a particular list of variables or array names. The first character in each record to be read must be blank. The second character in the first record of a list x must be an ampersand '&', immediately followed by the NAMELIST name x. The NAMELIST name must be followed by a blank. This name is followed by data items separated by commas. The end of a data list is signalled by '&END'.

For the present program the data is divided into three groups (lists x) called LINKS, METHOD and LIMITS. The list of variables and arrays in each is as follows:

**Data Group LINKS**

- **NLOOP**
  the number of loops in the linkage.

- **MAXARC**
  the maximum number of arcs in any of the loops.

- **ILINK, ILOOP**
  the arrays containing the topological description as defined in reference [3].

- **ARCL**
  array containing the lengths of the arcs.

- **GAMA**
  array containing the arc angles in degrees.
NOUTLK: the number in its own loop of the arc common with the output arc. It is negative if the output arc is measured from the start of NOUTLK.

NOUTLP: the number of the loop containing NOUTLK.

OUTLK: the length of the output arc.

OUTANG: output arc angle.

IUNITS: 1 if the arc lengths are in millimeters, 2 if the arc lengths are in inches.

Data Group \textbf{METHOD}

\begin{tabular}{ll}
CRNKI & input reference angle. \\
CRNKD & input angular velocity. \\
NDES or NPOINT & the number of input link positions. \\
DELT & array of input positions measured from the reference position. \\
MOTION & 0 if output is given by x-y cartesian coordinates of a point on the output arc \\
& 1 if the output is the angular position of the output arc. \\
& 2 if the output is given by the polar coordinates of a point on the output arc. \\
& 3 if the output is the linear position of a sliding output link. \\
\end{tabular}
IDEL  0 if output is to be computed at equally spaced input positions
      1 if output is to be computed at input positions specified in DELT

Data Group LIMITS

ORIGLK, ORING  polar coordinates of input link pivot.
OUTOLX, OUTOLY output tolerance in x- and y-directions
      if MOTION = 0.
OUTOLA  output tolerance in degrees, if MOTION = 1.
OUTOLR, OUTOLT output tolerance in polar coordinate
directions, MOTION = 2.
OUTOLS  output tolerance, if MOTION = 3.
IANG  same as MOTION
COSTA  array containing cost-tolerance constants
       $B_i$ for arc lengths parameters.
COSTG  array containing cost-tolerance constants
       for arc angle parameters.
LAST  0 if this is not the last set of input data, i.e. another follows
      1 if this is the last set of data.
SAMPLE INPUT DATA

I of DATA at 17:22:50 on JUL 27, 1982 for CCid=MCBB

FOUR-BAR SINE FUNCTION GENERATOR
&LINKS NLOOP=1, MAXARC=4, ILINK=1, -2, -3, 4, ILOOP=1, 0, 0, 1, ARCL=2.06980, 2.42146, 0.74613, 1.0, NOUTLK=3, NOUTLP=1, OUTANG=287.148, IUNITS=2 &END
&METHD MOTION=1, CRNKI=296.211, NPOINT=19, IDEL=1, CRNKD=1.0, DELT=0.0, 0.5, 1.0, 2.0, 2.5, 0.0, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5, 9.0 &END
&LIMITS IANG=1, TANGLE=65.0, OUTOLA=1.0, COSTA=4.2, 6.1, 0.5, 1.0, 101.0, COSTG=4.0, 0.2, 2.5, 2.25, 4.0, 98.0 &END

SLIDER CRANK MECHANISM
&LINKS NLOOP=1, MAXARC=4, ILINK=1, -2, -3, 4, ILOOP=1, 0, 0, 1, ARCL=50.0, 200.0, 250.0, 260.0, GAMAD=4.0, 0, NOUTLK=3, NOUTLP=1, &END
&METHD MOTION=3, CRNKI=270.0, NPOINT=37, IDEL=1, CRNKD=1.0, DELT=0.0, 10.0, 20.0, 30.0, 40.0, 50.0, 60.0, 70.0, 80.0, 90.0, 100.0, 110.0, 120.0, 130.0, 140.0, 150.0, 160.0, 170.0, 180.0, 190.0, 200.0, 210.0, 220.0, 230.0, 240.0, 250.0, 260.0, 270.0, 280.0, 290.0, 300.0, 310.0, 320.0, 330.0, 340.0, 350.0, 360.0 &END
&LIMITS OUTOLS=0.25, COSTA=100.0, 160.0, 1.0, 100.0 &END

SIX-BAR SINE FUNCTION GENERATOR
&LINKS NLOOP=2, MAXARC=5, ILINK=1, -2, -3, 4, 0, 1, -2, -3, 4, -4, ILOOP=1, 0, 0, 1, 0, 1, 0, 0, 1, ARCL=7.5, 30.139, 21.116, 36.716, 0.0, 7.5, 28.833, 21.421, 61.832, 39.998, GAMA=6.0, 4.0, 179.99, 12.0, 0, NOUTLK=4, NOUTLP=1, &END
&METHD MOTION=1, CRNKI=121.333, NPOINT=37, IDEL=1, CRNKD=1.0, DELT=0.0, 5.0, 10.0, 15.0, 20.0, 25.0, 30.0, 35.0, 40.0, 45.0, 50.0, 55.0, 60.0, 65.0, 70.0, 75.0, 80.0, 85.0, 90.0, 95.0, 100.0, 105.0, 110.0, 115.0, 120.0, 125.0, 130.0, 135.0, 140.0, 145.0, 150.0, 155.0, 160.0, 165.0, 170.0, 175.0, 180.0 &END
&LIMITS OUTOLA=0.5, COSTA=100.0, 150.0, 1.0, 10.0, 20.0, 25.0, 1.0, 10.0, 15.0, 10.0, 60.0, 25.0, COSTG=6.1, 10.0, 2.1, 2.0, 25.0, 25.0, 1.0, 10.0, 60.0 &END

TEN-BAR NEEDLE MECHANISM
&LINKS NLOOP=4, MAXARC=6, ILINK=1, 2, 3, 4, 0, 0, 1, 2, 3, -4, 0, 1, 2, -3, 4, -3, 4, 1, 2, 3, -4, 5, 4, 76.0, ILOOP=1, 0, 0, 1, 0, 0, 1, 1, 2, 0, 0, 1, 1, 1, 2, 3, 0, 0, 1, 176.0, ARCL=19.0, 95.0, 104.5, 112.4681, 0.0, 0.0, 0.0, 0.0, 0.0, 105.0, 31.0, 110.0, 0639.0, 0.0, 0.0, 0.0, 0.0, 19.0, 0.0, 105.0, 631.0, 12.5, 24.0, 0.0, 112.4681, 19.0, 105.0, 631.0, 245.5, 85.0, 352.7155, 76.0, GAMA=9.0, 0, 633.934, 640.0, 47.3389, 640.0, 20.0, 4425, 76.0, 0, NOUTLK=5, NOUTLP=4, OUTLK=121.6, OUTANG=10.0484, IUNITS=1 &END
&METHD MOTION=1, CRNKI=121.6409, DELT=0.0, 0.0, 15.0, 30.0, 45.0, 60.0, 75.0, 90.0, 105.0, 200.0, 100.0, 135.0, 150.0, 165.0, 180.0, 195.0, 210.0, 210.0, 240.0, 255.0, 270.0, 285.0, 300.0, 315.0, 330.0, 345.0, 360.0, 360.0, 360.0, 360.0, NDESS=25 &END
&LIMITS KTHETA=2, OUTOLA=1.0, COSTA=1.0, COSTA=1.0, 25.0, 30.0, 36.0, 240.0, 1.0, 30.0, 2.3, 36.0, 240.0, 1.0, 30.0, 9.5, 0.0, 3.0, 36.0, 1.0, 30.0, 9.5, 170.0, 20.0, 350.0, 810.0, COSTG=9.0, 0.0, 5.6, 0.0, 0.75, 6.0, 0.0, 2.4, 5.0, 0.0, 4.0, 78.0 &END

LAST=1 &END
APPENDIX I C

LISTING OF COMPUTER PROGRAM

PSODPLOTS
C PROGRAM FOR PLOTTING OUTPUT SENSITIVITIES TO PARAMETER AND OUTPUT DEVIATION AGAINST CRANK INPUT POSITION

IMPLICIT REAL*8(D,P,T,O), LOGICAL*L
DIMENSION DELT(37), DEVT(37), DEVS(37), DELX(37), DEVR(37),
1    DEV(37), DEVS(37), STEP(37), ERPX(37), ERNX(37),
2    ERPY(37), ERNY(37), ERPA(37), ERNA(37), ERPX(37),
3    ERNX(37), ERPT(37), ERNT(37), ERPS(37), ERNS(37),
4    PDX(37,100), SMX(37,100), PDY(37,100), SMY(37,100),
5    PDGX(37,100), SMGX(37,100), PDGY(37,100), SMGY(37,100),
6    PDOLX(37), SMOLX(37), PDOLY(37), SMOLY(37), PDOLX(37),
7    SMOLY(37), PDOLY(37), PDOLX(37), SMOLX(37),
8    PDORLY(37), SNO ORGY(37), PDORGY(37), SNO ORGX(37),
9    PDORGX(37), SNO ORGY(37), PDCRX(37), SNC RX(37),
10   PDCRY(37), SNC RX(37), VAR(37), LTITLE(72)

C --------- READ IN DATA
C
READ (7) LTITLE
READ (7) MOTHY NDES, IUNITS, MAXARC, NLOOP, KKL
READ (7) (DELT(I),I=1,NDES)
C
DO 10 K = 1, NDES
    STEP(K) = DELT(K)
C
GO TO (20, 50, 80, 110), MOTH
C
20 READ (7) OUTOLX, OUTOLY, (DEVX(I),I=1,NDES), (DEVY(J),J=1,NDES),
     (DEVX(I),I=1,NDES), (DEVY(J),J=1,NDES),
     1    ((PDX(I,J),I=1,NDES), (PDY(I,J),I=1,NDES),J=1,KKL),
     2    ((PDGX(I,J),I=1,NDES), (PDGY(I,J),I=1,NDES),J=1,KKL),
     3    ((PDOLX(I,J),I=1,NDES), (PDOLY(I,J),I=1,NDES),
     4    (PDOLX(I,J),I=1,NDES), (PDOLY(I,J),I=1,NDES),
     5    (PDOLX(I,J),I=1,NDES), (PDOLY(I,J),I=1,NDES),
     6    (PDORGX(I,J),I=1,NDES), (PDORGY(I,J),I=1,NDES),
     7    (PDORGX(I,J),I=1,NDES), (PDORGY(I,J),I=1,NDES),
     8    (PDORGX(I,J),I=1,NDES), (PDORGY(I,J),I=1,NDES),
     9    (PDORGX(I,J),I=1,NDES), (PDORGY(I,J),I=1,NDES),
    10   (PDORGX(I,J),I=1,NDES)
C
ADEVX = OUTOLX
ADEVY = OUTOLY
VSCALX = 1.2 * ADEVX
VSCALY = 1.2 * ADEVY
C
DO 30 I = 1, NDES
     ERPX(I) = DEVX(I)
     ERNX(I) = -ERPX(I)
     ERPY(I) = DEVY(I)
     ERNY(I) = -ERPY(I)
     SMOLX(I) = PDOLX(I)
     SMOLY(I) = PDOLY(I)
     SNO GX(I) = PDOLX(I)
     SNO GY(I) = PDOLY(I)
     SMORGX(I) = PDORGX(I)
     SMORY(I) = PDORGY(I)
     SMORGX(I) = PDORGX(I)
     SMORGY(I) = PDORGY(I)
     SNC RX(I) = PDCRX(I)
     PDCRY(I) = PDCRX(I)
Listing of PSODPLOTS at 17:26:38 on JUL 23, 1982 for CCid=MC88

SNCRY(I) = PDCRY(I)
30 CONTINUE
C
DO 40 J = 1, KKL
DO 40 I = 1, NDES
SNX(I,J) = PDX(I,J)
SHY(I,J) = PDY(I,J)
SNOX(I,J) = PDX(I,J)
SNGY(I,J) = PDY(I,J)
40 CONTINUE
GO TO 140
C
50 READ (7) OUTOLA, (DEVA(I),I=1,NDES), ((PDX(I,J),I=1,NDES),J=1,KKL)
1 , ((PDY(I,J),I=1,NDES),J=1,KKL), (PDCGX(I),I=1,NDES),
2 (PDCRX(I),I=1,NDES)
C
ADEVA = OUTOLA
VSCALA = 1.2 * ADEVA
C
DO 60 I = 1, NDES
ERPA(I) = DEVA(I)
ERMA(I) = -ERPA(I)
SNOGX(I) = PDCGX(I)
SNCRX(I) = PDCRX(I)
60 CONTINUE
C
DO 70 J = 1, KKL
DO 70 I = 1, NDES
SNX(I,J) = PDX(I,J)
SNGX(I,J) = PDGY(I,J)
70 CONTINUE
C
80 READ (7) OUTOLR, OUTOLT, (DEVr(I),I=1,NDES), (DEVt(J),J=1,NDES),
1 ((PDX(I,J),I=1,NDES),J=1,KKL), ((PDY(I,J),I=1,NDES),J=1,KKL),
2 ((PDGX(I,J),I=1,NDES),J=1,KKL), ((PDGY(I,J),I=1,NDES),J=1,
3 KKL), (PDLX(I),I=1,NDES), (PDLy(I),I=1,NDES),
4 (PDGX(I),I=1,NDES), (PDGY(I),I=1,NDES), (PDOLX(I),I=1,
5 NDES), (PDORLX(I),I=1,NDES), (PDORBX(I),I=1,NDES),
6 (PDORXY(I),I=1,NDES), (PDOLX(I),I=1,NDES), (PDCRX(I),I=1,
7 NDES)
C
ADEVR = OUTOLR
ADEVT = OUTOLT
VSCLAR = 1.2 * ADEVR
VSCALT = 1.2 * ADEVT
C
DO 90 I = 1, NDES
ERPR(I) = DEVr(I)
ERMR(I) = -ERPR(I)
ERPT(I) = DEVt(I)
ERNt(I) = -ERPT(I)
SNOLX(I) = PDLX(I)
SNOly(I) = PDLy(I)
SNOGX(I) = PDGX(I)
SNOGY(I) = PDGY(I)
200

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117 SNORLX(I) = PDORLX(I)
118 SNORLY(I) = PDORLY(I)
119 SNORGX(I) = PDORGX(I)
120 SNORGY(I) = PDORGY(I)
121 SNCRX(I) = PDCRX(I)
122 SNCRY(I) = PDCRY(I)
123 90 CONTINUE
124 DO 100 J = 1, KKL
125 DO 100 I = 1, NDES
126 SNX(I, J) = PDX(I, J)
127 SNY(I, J) = PDY(I, J)
128 SNGX(I, J) = PDGX(I, J)
129 SNGY(I, J) = PDGY(I, J)
130 100 CONTINUE
131 100 CONTINUE
132 C
133 DO 140 I = 1, NDES
134 READ (7) OUTOLS, (DEVS(I), I=1, NDES), ((PDX(I, J), I=1, NDES), J=1, KKL)
135 1, ((PDGX(I, J), I=1, NDES), J=1, KKL), (PDCRX(I), I=1, NDES)
136 C
137 ADEVS = OUTOLS
138 VSCALX = 1.2 * ADEVS
139 C
140 DO 120 I = 1, NDES
141 ERPS(I) = DEVS(I)
142 ERNS(I) = -ERPS(I)
143 SNCRX(I) = PDCRX(I)
144 120 CONTINUE
145 120 CONTINUE
146 C
147 DO 130 J = 1, KKL
148 DO 130 I = 1, NDES
149 SNX(I, J) = PDX(I, J)
150 SNGX(I, J) = PDGX(I, J)
151 130 CONTINUE
152 C
153 C---------- PLOT GRAPHS
154 C
155 140 XNTR = 0.1 * (STEP(NDES) - STEP(1))
156 MORT = 1
157 C
158 CALL PAPER(1)
159 C
160 GO TO (150, 400, 480, 730), MORT
161 C
162 150 CALL SETPLS(STEP, XNTR, NDES, VSCALX, IUNITS, MORT, MORT, LTITLE)
163 C
164 CALL CTRSET(2)
165 CALL PLOTC5(STEP(1), 1.1*VSCALX, 'OUTPUT DEVIATION IN ', 20)
166 CALL TYPECS('X-DIRECTION', 11)
167 CALL BROKEN(5, 10, 5, 10)
168 CALL POSITN(STEP(1), ADEVX)
169 CALL JOIN(STEP(NDES), ADEVX)
170 CALL POSITN(STEP(1), -ADEVX)
171 CALL JOIN(STEP(NDES), -ADEVX)
172 CALL FULL
173 CALL CTRSET(4)
174 CALL THICK(1)
Listing of PSODPLOTS at 17:26:38 on JUL 23, 1982 for CCid=MCBB

175 CALL PTPLOT(STEP, ERFX, 1, NDES, 54)
176 CALL THICK(3)
177 CALL NSCURV(STEP, ERFX, 1, NDES)
178 CALL THICK(1)
179 CALL PTPLOT(STEP, ERNX, 1, NDES, 54)
180 CALL THICK(3)
181 CALL NSCURV(STEP, ERNX, 1, NDES)
182 CALL FRAME
183 CALL SETPLS(STEP, XNTR, NDES, VSCALY, IUNITS, MOTH, NORT, LTITLE)
184 CALL CTRSET(2)
185 CALL PLOTCS(STEP(1), 1.1*VSCALY, 'OUTPUT DEVIATION IN Y', 20)
186 CALL TYPECS('Y-DIRECTION', 11)
187 CALL BROKEN(5, 10, 5, 10)
188 CALL POSITH(STEP(1), ADEVY)
189 CALL JOIN(STEP(NDES), ADEVY)
190 CALL POSITH(STEP(1), -ADEVY)
191 CALL JOIN(STEP(NDES), -ADEVY)
192 CALL FULL
193 CALL CTRSET(4)
194 CALL THICK(1)
195 CALL PTPLOT(STEP, ERPY, 1, NDES, 34)
196 CALL THICK(3)
197 CALL NSCURV(STEP, ERPY, 1, NDES)
198 CALL THICK(1)
199 CALL PTPLOT(STEP, ERNY, 1, NDES, 54)
200 CALL THICK(3)
201 CALL NSCURV(STEP, ERNY, 1, NDES)
202 CALL FRAME
203 CALL SETPLS(STEP, XNTR, NDES, VSCALY, IUNITS, MOTH, NORT, LTITLE)
204 CALL CTRSET(2)
205 CALL PLOTCS(STEP(2), 1.05*VORD, 'SENSITIVITY IN X-DIRECTION', 26)
206 CALL TYPECS('X-DIRECTION', 11)
207 CALL POSITH(STEP(1), ADEVX)
208 CALL JOIN(STEP(NDES), ADEVX)
209 CALL POSITH(STEP(1), -ADEVX)
210 CALL JOIN(STEP(NDES), -ADEVX)
211 CALL FULL
212 CALL CTRSET(4)
213 CALL THICK(1)
214 CALL PTPLOT(STEP, VAR, 1, NDES, 54)
215 CALL THICK(3)
216 CALL NSCURV(STEP, VAR, 1, NDES)
217 CALL SYMNEY(STEP, VORD, XNTR, NDES, NAR, NLP, MAS, 11)
218 CALL CTRORI(1.0)
219 CALL POSITH(-1.75*XNTR, 0.325*VORD)
220 CALL TYPECS('H/M', 11)
221 CALL CTRORI(0.0)
222 CALL YSCALE(SNX, VORD, NDES, KKL, MAXARC, J)
223 CALL PAXES(STEP, XNTR, VORD, NDES, LTITLE)
224 CALL PLOTCS(STEP(2), 1.05*VORD, 'SENSITIVITY IN X-DIRECTION', 26)
225 CALL CTRSET(4)
226 CALL THICK(1)
227 CALL PTPLOT(STEP, VAR, 1, NDES, MAS)
228 CALL THICK(2)
229 CALL NSCURV(STEP, VAR, 1, NDES)
230 CALL SYMNEY(STEP, VORD, XNTR, NDES, NAR, NLP, MAS, 11)
231 CALL CTRORI(1.0)
232 CALL POSITH(-1.75*XNTR, 0.325*VORD)
233 CALL TYPECS('H/M', 11)
234 CALL CTRORI(0.0)
235 CALL YSCALE(SNX, VORD, NDES, KKL, MAXARC, J)
236 CALL PAXES(STEP, XNTR, VORD, NDES, LTITLE)
237 CALL PLOTCS(STEP(2), 1.05*VORD, 'SENSITIVITY IN X-DIRECTION', 26)
238 CALL CTRSET(4)
239 CALL THICK(1)
240 CALL PTPLOT(STEP, VAR, 1, NDES, 54)
241 CALL THICK(3)
242 CALL NSCURV(STEP, VAR, 1, NDES)
243 CALL SYMNEY(STEP, VORD, XNTR, NDES, NAR, NLP, MAS, 11)
244 CALL CTRORI(1.0)
245 CALL POSITH(-1.75*XNTR, 0.325*VORD)
246 CALL TYPECS('H/M', 11)
247 CALL CTRORI(0.0)
248 CALL YSCALE(SNX, VORD, NDES, KKL, MAXARC, J)
249 CALL PAXES(STEP, XNTR, VORD, NDES, LTITLE)
250 CALL PLOTCS(STEP(2), 1.05*VORD, 'SENSITIVITY IN X-DIRECTION', 26)
251 CALL CTRSET(4)
252 CALL THICK(1)
253 CALL PTPLOT(STEP, VAR, 1, NDES, MAS)
254 CALL THICK(2)
255 CALL NSCURV(STEP, VAR, 1, NDES)
256 CALL SYMNEY(STEP, VORD, XNTR, NDES, NAR, NLP, MAS, 11)
257 CALL CTRORI(1.0)
258 CALL POSITH(-1.75*XNTR, 0.325*VORD)
259 CALL TYPECS('H/M', 11)
260 CALL CTRORI(0.0)
261 CALL YSCALE(SNX, VORD, NDES, KKL, MAXARC, J)
262 CALL PAXES(STEP, XNTR, VORD, NDES, LTITLE)
263 CALL PLOTCS(STEP(2), 1.05*VORD, 'SENSITIVITY IN X-DIRECTION', 26)
264 CALL CTRSET(4)
265 CALL THICK(1)
266 CALL PTPLOT(STEP, VAR, 1, NDES, 54)
267 CALL THICK(3)
268 CALL NSCURV(STEP, VAR, 1, NDES)
269 CALL SYMNEY(STEP, VORD, XNTR, NDES, NAR, NLP, MAS, 11)
270 CALL CTRORI(1.0)
271 CALL POSITH(-1.75*XNTR, 0.325*VORD)
272 CALL TYPECS('H/M', 11)
273 CALL CTRORI(0.0)
274 CALL YSCALE(SNX, VORD, NDES, KKL, MAXARC, J)
275 CALL PAXES(STEP, XNTR, VORD, NDES, LTITLE)
276 CALL PLOTCS(STEP(2), 1.05*VORD, 'SENSITIVITY IN X-DIRECTION', 26)
277 CALL CTRSET(4)
278 CALL THICK(1)
279 CALL PTPLOT(STEP, VAR, 1, NDES, MAS)
280 CALL THICK(2)
281 CALL NSCURV(STEP, VAR, 1, NDES)
282 CALL SYMNEY(STEP, VORD, XNTR, NDES, NAR, NLP, MAS, 11)
283 CALL CTRORI(1.0)
284 CALL POSITH(-1.75*XNTR, 0.325*VORD)
285 CALL TYPECS('H/M', 11)
286 CALL CTRORI(0.0)
287 CALL YSCALE(SNX, VORD, NDES, KKL, MAXARC, J)
288 CALL PAXES(STEP, XNTR, VORD, NDES, LTITLE)
289 CALL PLOTCS(STEP(2), 1.05*VORD, 'SENSITIVITY IN X-DIRECTION', 26)
290 CALL CTRSET(4)
291 CALL THICK(1)
292 CALL PTPLOT(STEP, VAR, 1, NDES, 54)
293 CALL THICK(3)
294 CALL NSCURV(STEP, VAR, 1, NDES)
295 CALL SYMNEY(STEP, VORD, XNTR, NDES, NAR, NLP, MAS, 11)
296 CALL CTRORI(1.0)
297 CALL POSITH(-1.75*XNTR, 0.325*VORD)
298 CALL TYPECS('H/M', 11)
299 CALL CTRORI(0.0)
300 CALL YSCALE(SNX, VORD, NDES, KKL, MAXARC, J)
301 CALL PAXES(STEP, XNTR, VORD, NDES, LTITLE)
302 CALL PLOTCS(STEP(2), 1.05*VORD, 'SENSITIVITY IN X-DIRECTION', 26)
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233 YORD = 0.0
234 DO 190 I = 1, NDES
235 IF (SNOLX(I) .GT. YORD) YORD = SNOLX(I)
236 IF (SNRXLX(I) .GT. YORD) YORD = SNRXLX(I)
237 190 CONTINUE
238 IF (YORD .LT. 1.0D-9) GO TO 210
239 VORD = 1.1 - YORD
240 CALL FRAME
241 CALL PAXES(STEP, XMTR, VORD, NDES, LTITLE)
242 CALL PLOTCS(STEP, 1.05*VORD, 'SENSITIVITY IN X-DIRECTION', 26)
243 CALL CTRORI(1.0)
244 CALL POSITN(-1.75*XMTR, 0.325*VORD)
245 IF (IUNITS .EQ. 1) CALL TYPECS('( MM / MM )', 11)
246 IF (IUNITS .EQ. 2) CALL TYPECS('( IN / IN )', 11)
247 CALL CTRORI(0.0)
248 IF (SNOLX(I) .LT. - 5.0D-1) GO TO 200
249 CALL CTRORI(4)
250 CALL THICK(1)
251 CALL PIPLOT(STEP, SNOLX, 1, NDES, 51)
252 CALL THICK(2)
253 CALL NSCURV(STEP, SNOLX, 1, NDES)
254 CALL SYMBK(STEP, VORD, XMTR, NDES, 25, 1, 11)
255 200 IF (SNRXLX(I) .LT. - 5.0D-1) GO TO 210
256 CALL THICK(1)
257 CALL CTRORI(4)
258 CALL PIPLOT(STEP, SNRXLX, 1, NDES, 52)
259 CALL THICK(2)
260 CALL NSCURV(STEP, SNRXLX, 1, NDES)
261 CALL SYMBK(STEP, VORD, XMTR, NDES, 17, 11, 52)
262
263 210 MLP = 0
264 DO 240 J = 1, KKL
265 IF (J .EQ. MAXARC*MLP + 1) NGS = 0
266 IF (SNGX(I, J) .LT. - 5.0D-1) GO TO 240
267 NGS = NGS + 1
268 IF (J .LE. MAXARC*MLP .AND. NGS .GE. 1) GO TO 220
269 CALL FRAME
270 NAS = 49
271 CALL YSCALE(SNGX, VORD, NDES, KKL, MAXARC, J)
272 CALL PAXES(STEP, XMTR, VORD, NDES, LTITLE)
273 CALL PLOTCS(STEP, 1.03*VORD, 'SENSITIVITY IN X-DIRECTION', 26)
274 220 MLP = (J - 1) / MAXARC + 1
275 CALL-CTRORI(1:0)
276 CALL POSITN(-1.75*XMTR, 0.325*VORD)
277 IF (IUNITS .EQ. 1) CALL TYPECS('( MM / RAD )', 12)
278 IF (IUNITS .EQ. 2) CALL TYPECS('( IN / RAD )', 12)
279 CALL CTRORI(0.0)
280 230 CONTINUE
281 VAR(I) = SNGX(I, J)
282 NAS = NAS + 1
283 DO 230 I = 1, NDES
284
285
CALL SYMKEY(STEP, VORD, XMTR, NDES, MAT, NLP, HAS, 17)
240 CONTINUE
C
YORD = 0.0
DO 250 I = 1, NDES
  IF (SNOGX(I) .GT. YORD) YORD = SNOGX(I)
  IF (SNORGX(I) .GT. YORD) YORD = SNORGX(I)
  IF (SNCRX(I) .GT. YORD) YORD = SNCRX(I)
250 CONTINUE
VORD = 1.1 * YORD
CALL FRAME
CALL PAXES(STEP, XMTR, VORD, NDES, 'TITLE')
CALL PLOTCS(STEP(2), 1.05*VORD, 'SENSITIVITY IN X-DIRECTION', 12)
CALL CTORI(1.0)
CALL POSITN(-1.75*XMTR, 0.325*VORD)
IF (IUNITS EQ. 1) CALL TYPECS('( MM / MM )', 11)
IF (IUNITS EQ. 2) CALL TYPECS('( IN / IN )', 11)
CALL CTORI(0.0)
CALL PAXES(STEP, XMTR, VORD, NDES, 'TITLE')
CALL PLOTCS(STEP(2), 1.05*VORD, 'SENSITIVITY IN Y-DIRECTION', 12)
CALL CTORI(1.0)
CALL PCSITM(-1.75*XMTR, 0.325*VORD)
IF (IUNITS EQ. 1) CALL TYPECS('( MM / MM )', 11)
IF (IUNITS EQ. 2) CALL TYPECS('( IN / IN )', 11)
CALL CTORI(0.0)
280 NLP = 0
DO 300 J = 1, KKL
  IF (SNY(J) .LT. -5.0D-1) GO TO 300
  IF (J LE. MAXARC*NLP) GO TO 280
CALL FRAME
HAS = 49
CALL YSCALE(SNY, VORD, NDES, KKL, MAXARC, J)
CALL PAXES(STEP, XMTR, VORD, NDES, 'TITLE')
CALL PLOTCS(STEP(2), 1.05*VORD, 'SENSITIVITY IN Y-DIRECTION', 12)
290 CALL CTORI(1.0)
CALL POSITN(-1.75*XMTR, 0.325*VORD)
292 290 NLP = (J - 1) / MAXARC + 1
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349   VAR(I) = SNY(I,J)
350 290   CONTINUE
351   CALL THICK(1)
352   CALL CTRSET(4)
353   CALL PTPLT(STEP, VAR, 1, NDES, MAS)
354   CALL THICK(2)
355   CALL NSCURV(STEP, VAR, 1, NDES)
356   CALL SYMBK(STEP, VORD, XMTR, NDES, MAR, NLP, MAS, 11)
357 300 CONTINUE
358
359   YORD = 0.0
360   DO 310 I = 1, NDES
361      IF (SNOLY(I) .GT. YORD) YORD = SNOLY(I)
362      IF (SNORLY(I) .GT. YORD) YORD = SNORLY(I)
363 310 CONTINUE
364   IF (YORD .LT. 1.0D-9) GO TO 330
365   VORD = 1.1 * YORD
366   CALL FRAME
367   CALL PAXES(STEP, XMTR, VORD, NDES, LTITLE)
368   CALL PLOTCS(STEP(2), 1.05*VORD, 'SENSITIVITY IN Y-DIRECTION', 26)
369   CALL CTRORI(1.0)
370   CALL POSITN(-1.75*XMTR, 0.325*VORD)
371   IF (JUNITS .EQ. 1) CALL TYPECS('( MM / MM )', 11)
372   IF (JUNITS .EQ. 2) CALL TYPECS('( IN / IN )', 11)
373   CALL CTRORI(0.0)
374   IF (SNOLY(I) .LT. - 5.0D-1) GO TO 320
375   CALL CTRSET(4)
376   CALL THICK(1)
377   CALL PTPLT(STEP, SNOLY, 1, NDES, 51)
378   CALL THICK(2)
379   CALL NSCURV(STEP, SNOLY, 1, NDES)
380   CALL SYMBK(STEP, VORD, XMTR, NDES, 25, 11, 51)
381 320 IF (SNOLY(I) .LT. - 5.0D-1) GO TO 330
382   CALL THICK(1)
383   CALL CTRSET(4)
384   CALL PTPLT(STEP, SNORLY, 1, NDES, 52)
385   CALL THICK(2)
386   CALL NSCURV(STEP, SNORLY, 1, NDES)
387   CALL SYMBK(STEP, VORD, XMTR, NDES, 17, 11, 52)
388
389   NLP = 0
390   DO 360 J = 1, KKL
391      IF (J .EQ. MAXARC*NLP + 1) NGG = 0
392      IF (SNGY(1,J) .LT. 5.0D-1) GO TO 360
393         NGG = NGG + 1
394      IF (J .LE. MAXARC*NLP AND. NOS .LT. 0) GO TO 340
395   CALL FRAME
396   CALL YSCALE(SNGY, VORD, NDES, KKL, MAXARC, J)
397   CALL PAXES(STEP, XMTR, VORD, NDES, LTITLE)
398   CALL PLOTCS(STEP(2), 1.05*VORD, 'SENSITIVITY IN Y-DIRECTION', 26)
399      CALL CTRORI(1.0)
400      CALL POSITN(-1.75*XMTR, 0.325*VORD)
401      IF (JUNITS .EQ. 1) CALL TYPECS('( MM / RAD )', 12)
402      IF (JUNITS .EQ. 2) CALL TYPECS('( IN / RAD )', 12)
403      CALL CTRORI(0.0)
404 340   NLP = (J - 1) / MAXARC + 1
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NAR = J - (NLP - 1) * MAXARC
NAS = NAS + 1
DO 350 I = 1, NDES
   VAR(I) = SNOG(I,J)
350 CONTINUE
CALL THICK(1)
CALL CTRSET(4)
CALL PTPLOT(STEP, VAR, 1, NDES, NAS)
CALL THICK(2)
CALL NSCURV(STEP, VAR, 1, NDES)
CALL SYMKY(STEP, VORD, XMTR, NDES, NAR, NLP, NAS, 17)
360 CONTINUE

DO 370 I = 1, NDES
   IF (SNOG(I) .GT. YORD) YORD = SNOG(I)
   IF (SNOR(I) .GT. YORD) YORD = SNOR(I)
   IF (SNCRY(I) .GT. YORD) YORD = SNCY(I)
370 CONTINUE
VORD = 1.1 * YORD
CALL FRAME
CALL PAXES(STEP, XMTR, VORD, NDES, LTITLE)
CALL PLOTCS(STEP(2), 1.05*VORD, 'SENSITIVITY IN Y-DIRECTION', 26)
CALL CTRORI(1.0)
CALL POSITN(-1.75*XMTR, 0.325*VORD)
IF ( IUNITS .EQ. 1) CALL TYPECS( 'MM / RAD ', 12)
IF ( IUNITS .EQ. 2) CALL TYPECS( 'IN / RAD ', 12)
CALL CTRORI(0.0)
IF (SNOGY(I) .LT. -5.0D-1) GO TO 380
CALL THICK(1)
CALL CTRSET(4)
CALL PTPLOT(STEP, SNOG, 1, NDES, 51)
CALL THICK(2)
CALL NSCURV(STEP, SNOG, 1, NDES)
CALL SYMKY(STEP, VORD, XMTR, NDES, 25, 17, 51)
380 IF (SNORY(I) .LT. -5.0D-1) GO TO 390
CALL THICK(1)
CALL CTRSET(4)
CALL PTPLOT(STEP, SNOR, 1, NDES, 52)
CALL THICK(2)
CALL NSCURV(STEP, SNOR, 1, NDES)
CALL SYMKY(STEP, VORD, XMTR, NDES, 17, 17, 52)
390 CALL THICK(1)
CALL CTRSET(4)
CALL PTPLOT(STEP, SNCY, 1, NDES, 53)
CALL THICK(2)
CALL NSCURV(STEP, SNCY, 1, NDES)
CALL SYMKY(STEP, VORD, XMTR, NDES, 13, 17, 53)
C
GO TO 810
C
400 CALL SETPLS(STEP, XMTR, NDES, VSCALA, IUNITS, MOTN, NORT, LTITLE)
C
CALL CTRSET(2)
CALL BROKEN(5, 10, 5, 10)
CALL POSITN(STEP(1), ADEVA)
CALL JOIN(STEP(NDES), ADEVA)
CALL POSITN(STEP(1), -ADEVA)
CALL JOIN(STEP, NDES), -ADEVA)
CALL FULL
CALL CTRSET(4)
CALL THICK(1)
CALL PTPLOT(STEP, ERPA, 1, NDES, 54)
CALL THICK(3)
CALL NSCURV(STEP, ERPA, 1, NDES)
CALL THICK(11)
CALL PTPLOT(STEP, ERNA, 1, NDES, 54)
CALL THICK(3)
CALL NSCURV(STEP, ERNA, 1, NDES)

C
NLP = 0
DO 430 J = 1, KKL
IF (SNX(I, J) .LT. - 5.0D-1) GO TO 430
IF (J .LE. MAXARC*NLP) GO TO 410
CALL FRAME
MAS = 49
CALL YSCALE(SNX, VORD, NDES, KKL, MAXARC, J)
CALL PAXES(STEP, XMTR, VORD, NDES, LTITLE)
CALL CTRORI(1.0)
CALL POSTIN(-1.75*XMTR, 0.325*VORD)
IF (IUNITS .EQ. 1) CALL TYPECS(' (RAD / MM )', 12)
IF (IUNITS .EQ. 2) CALL TYPECS(' (RAD / IN )', 12)
CALL CTRORI(0.0)
410 NLP = (J - 1) / MAXARC + 1
NAR = J - (NLP - 1) * MAXARC
MAS = MAS + 1
DO 420 I = 1, NDES
VAR(I) = SNX(I, J)
420 CONTINUE
CALL THICK(1)
CALL CTRSET(4)
CALL PTPLOT(STEP, VAR, 1, NDES, MAS)
CALL THICK(2)
CALL NSCURV(STEP, VAR, 1, NDES)
CALL SYNKEY(STEP, VORD, XMTR, NDES, NAR, NLP, MAS, 11)
430 CONTINUE

C
NLP = 0
DO 460 J = 1, KKL
IF (J .EQ. MAXARC*NLP + 1) NGB = 0
IF (SMGX(I, J) .LT. - 5.0D-1) GO TO 460
NGB = NGB + 1
IF (J .LE. MAXARC*NLP .AND. NGB .NE. 1) GO TO 440
CALL FRAME
MAS = 49
CALL YSCALE(SMGX, VORD, NDES, KKL, MAXARC, J)
CALL PAXES(STEP, XMTR, VORD, NDES, LTITLE)
CALL CTRORI(1.0)
CALL POSTIN(-1.75*XMTR, 0.325*VORD)
CALL TYPECS(' (RAD / RAD )', 13)
CALL CTRORI(0.0)
440 NLP = (J - 1) / MAXARC + 1
NAR = J - (NLP - 1) * MAXARC
MAS = MAS + 1
DO 450 I = 1, NDES
VAR(I) = SMGX(I, J)
450 CONTINUE
Listing of PSODPLOTS at 17:26:38 on JUL 23, 1982 for CCid=NCDB

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523 450 CONTINUE
524 CALL THICK(1)
525 CALL CTRSET(4)
526 CALL PTPLOT(STEP, VAR, 1, NDES, NAS)
527 CALL THICK(2)
528 CALL NSCURV(STEP, VAR, 1, NDES)
529 CALL SYMKY(STEP, VORD, XMTR, NDES, NAR, NLP, NAS, 17)
530 460 CONTINUE
531
532 C
533 YORD = 0.0
534 DO 470 I = 1, NDES
535 IF (SN0GX(I) .GT. YORD) YORD = SN0GX(I)
536 IF (SNR0X(I) .GT. YORD) YORD = SNR0X(I)
537 470 CONTINUE
538 VORD = 1.1 * YORD
539 CALL FRAME
540 CALL PAXES(STEP, XMTR, VORD, NDES, LTITLE)
541 CALL CTRORI(1.0)
542 CALL POSIM(-1.75*XMTR, 0.325*VORD)
543 CALL TYPECS('RAD / RAD', 13)
544 CALL CTRORI(0.0)
545 CALL THICK(1)
546 CALL CTRSET(4)
547 CALL PTPLOT(STEP, SN0GX, 1, NDES, 51)
548 CALL THICK(2)
549 CALL NSCURV(STEP, SN0GX, 1, NDES)
550 CALL SYMKY(STEP, VORD, XMTR, NDES, 25, 17, 51)
551 CALL THICK(1)
552 CALL CTRSET(4)
553 CALL PTPLOT(STEP, SNCRX, 1, NDES, 52)
554 CALL THICK(2)
555 CALL NSCURV(STEP, SNCRX, 1, NDES)
556 CALL SYMDXY(STEP, VORD, XMTR, NDES, 13, 17, 52)
557 C
558 60 TO 810
559 480 CALL SETPLS(STEP, XMTR, NDES, VSCALR, IUNITS, MOTN, NORT, LTITLE)
560 C
561 CALL CTRSET(2)
562 CALL PLTC3S(STEP(1), 1.1*VSCALR, 'OUTPUT DEVIATION IN ', 21)
563 CALL TYPECS('RADIAL DIRECTION', 16)
564 CALL BROKEN(5, 10, 5, 10)
565 CALL POSIM(STEP(1), ADEVR)
566 CALL JOIN(STEP(NDES), ADEVR)
567 CALL POSIM(STEP(1), -ADEVR)
568 CALL JOIN(STEP(NDES), -ADEVR)
569 CALL FULL
570 CALL CTRSET(4)
571 CALL THICK(1)
572 CALL PTPLOT(STEP, ERPR, 1, NDES, 54)
573 CALL THICK(3)
574 CALL NSCURV(STEP, ERPR, 1, NDES)
575 CALL THICK(1)
576 CALL PTPLOT(STEP, ERMR, 1, NDES, 54)
577 CALL THICK(3)
578 CALL NSCURV(STEP, ERMR, 1, NDES)
579 C
580 CALL FRAME
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Listing of PSODPLOTS at 17:26:38 on JUL 23, 1982 for CCid=MCBB

581  MORT = 2
582  CALL SETPLS(STEP, XMTR, NDES, VSCALT, IUNITS, HOTH, MORT, LTITLE)
583  CALL CTRSET(2)
584  CALL PLOTCS(STEP(1), 1.1*VSCALT, 'OUTPUT DEVIATION IN ', 21)
585  CALL TYPECS('POLAR ANGLE', 11)
586  CALL BROKEN(5, 10, 5, 10)
587  CALL POSITN(STEP(1), ADEV)
588  CALL JOIN(STEP(NDES), ADEV)
589  CALL POSITN(STEP(1), -ADEV)
590  CALL JOIN(STEP(NDES), -ADEV)
591  CALL FULL
592  CALL CTRSET(4)
593  CALL THICK(1)
594  CALL PT PLOT(STEP, ERPT, 1, NDES, 54)
595  CALL THICK(3)
596  CALL NSCURV(STEP, ERPT, 1, NDES)
597  CALL THICK(1)
598  CALL PT PLOT(STEP, ERNT, 1, NDES, 54)
599  CALL THICK(3)
600  CALL NSCURV(STEP, ERNT, 1, NDES)
601  C
602  MLP = 0
603  DO 510 J = 1, KKL
604     IF (SNX(I,J) .LT. -5.0D-1) GO TO 510
605     IF (J .LE. MAXARC*MLP) GO TO 490
606     CALL FRAME
607     M H = 49
608     CALL YSCALE(SNX, VORD, MDES, KKL, MAXARC, J)
609     CALL PAXES(STEP, XMTR, VORD, NDES, LTITLE)
610     CALL PLOTCS(STEP(2), 1.05*VORD, 'SENSITIVITY IN POLAR RADIUS',
611       1, 27)
612     CALL CT ORI(1.0)
613     CALL POSITN(-1.75*XMTR, 0.325*VORD)
614     IF (IUNITS .EQ. 1) CALL TYPECS('(' MM / MM ')', 11)
615     IF (IUNITS .EQ. 2) CALL TYPECS('(' IN / IN ')', 11)
616     CALL CT ORI(0.0)
617     490  MLP = (J - 1) / MAXARC + 1
618     NAR = J - (MLP - 1) * MAXARC
619     M H = M H + 1
620     DO 500 I = 1, NDES
621        VAR(I) = SNX(I,J)
622     500  CONTINUE
623     CALL THICK(1)
624     CALL CTRSET(4)
625     CALL PT PLOT(STEP, VAR, 1, NDES, MAS)
626     CALL THICK(2)
627     CALL NSCURV(STEP, VAR, 1, NDES)
628     CALL SYMKEY(STEP, VORD, XMTR, NDES, NAR, MLP, MAS, 11)
629  510  CONTINUE

   C
630  YORD = 0.0
631  DO 520 I = 1, NDES
632     IF (SNOLX(I) .GT. YORD) YORD = SNOLX(I)
633     IF (SNORLX(I) .GT. YORD) YORD = SNORLX(I)
634  520  CONTINUE
635  IF (YORD .LT. 1.0D-9) GO TO 540
636  YORD = 1.1 * YORD
637  CALL FRAME
CALL PAXES(STEP, XMTR, VORD, NDES, LTITLE)
CALL PLOTCS(STEP(2), 1.05*VORD, 'SENSITIVITY IN POLAR RADIUS', 27)
CALL CTRORI(1.0)
CALL POSITN(-1.75*XMTR, 0.325*VORD)
IF (IUNITS .EQ. 1) CALL TYPECS('( MH / MM )', 11)
IF (IUNITS .EQ. 2) CALL TYPECS('( IN / IN )', 11)
CALL CTRORI(0.0)
IF (SNOLX(1).LT. -5.0D-1) GO TO 530
CALL CTRSET(4)
CALL THICK(1)
CALL PTPLOT(STEP, SNOLX, 1, NDES, 51)
CALL THICK(2)
CALL NSCURV(STEP, SNOLX, 1, NDES)
CALL SYXBKY(STEP, VORD, XMTR, NDES, 27)
IF (UUMITS EQ. 1) CALL TYPECS('( MH / HN )', 12)
IF (UUMITS EQ. 2) CALL TYPECS('( IN / IN )', 12)
CALL CTRORI(0.0)
DO 570 J = 1, NKL
IF (J .EQ. MAXARC*MLP + 1) MGG = 0
IF (J .LE. MAXARC*MLP AND MGG .NE. 1) GO TO 530
CALL FRAME
HAS = HAS + 1
DO 560 I = 1, NDES
VAR(I) = SNMGX(I,J)
560 CONTINUE
CALL THICK(1)
CALL CTRSET(4)
CALL PTPLOT(STEP, VAR, 1, NDES, NAS)
CALL THICK(2)
CALL NSCURV(STEP, VAR, 1, NDES)
CALL SYNKEY(STEP, VORD, XMTR, NDES, NAR, NLP, NAS, 17)
570 CONTINUE
CALL CTRORI(1.0)
CALL POSITN(-1.75*XMTR, 0.325*VORD)
IF (IUNITS .EQ. 1) CALL TYPECS('( MH / RAD )', 12)
IF (IUNITS .EQ. 2) CALL TYPECS('( IN / RAD )', 12)
CALL CTRORI(0.0)
550 NLP = (J - 1) / MAXARC + 1
550 NLP = (J - 1) / MAXARC + 1
550 NLP = (J - 1) / MAXARC + 1
NAR = J - (NLP - 1) * MAXARC
NAS = NAS + 1
DO 560 I = 1, NDES
VAR(I) = SNMGX(I,J)
560 CONTINUE
CALL THICK(1)
CALL CTRSET(4)
CALL PTPLOT(STEP, VAR, 1, NDES, NAS)
CALL THICK(2)
CALL NSCURV(STEP, VAR, 1, NDES)
CALL SYNKEY(STEP, VORD, XMTR, NDES, NAR, NLP, NAS, 17)
570 CONTINUE
YORD = 0.0
DO 580 I = 1, NDES
IF (SNMGX(I) .GT. YORD) YORD = SNMGX(I)
IF (SNCRX(I) .GT. YORD) YORD = SNCRX(I)
580 CONTINUE
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CONTINUE
VORD = 1.1 * YORD
CALL FRAME
CALL PAXES(STEP, XMTR, VORD, NDES, LTITLE)
CALL PLOTCS(STEP(2), 1.05*VORD, 'SENSITIVITY IN POLAR RADIUS', 27)
CALL CTRORI(1.0)
CALL POSITM(-1.75*XMTR, 0.325*VORD)
IF (IUNITS .EQ. 1) CALL TYPECS('( HM / RAD )', 12)
IF (IUNITS .EQ. 2) CALL TYPECS('( IN / RAD )', 12)
CALL CTRORI(0.0)
IF (SNOGX(1) .LT. - 5.0D-1) GO TO 590
CALL THICK(1)
CALL CTRSET(4)
CALL PTPTLOT(STEP, SNOGX, 1, NDES, 51)
CALL THICK(2)
CALL NSCURV(STEP, SNOGX, 1, NDES)
CALL SYMKEY(STEP, VORD, XMTR, NDES, 17, 25, 51)
590 IF (SNORGX(1) .LT. - 5.0D-1) GO TO 600
CALL THICK(1)
CALL CTRSET(4)
CALL PTPTLOT(STEP, SNORGX, 1, NDES, 52)
CALL THICK(2)
CALL NSCURV(STEP, SNORGX, 1, NDES)
CALL SYMKEY(STEP, VORD, XMTR, NDES, 17, 17, 52)
600 CALL THICK(1)
CALL CTRSET(4)
CALL PTPTLOT(STEP, SNCRX, 1, NDES, 53)
CALL THICK(2)
CALL NSCURV(STEP, SNCRX, 1, NDES)
CALL SYMKEY(STEP, VORD, XMTR, NDES, 13, 17, 53)
C
MLP = 6
DO 630 J = 1, KK1
   IF (SNY(I,J) .LT. - 3.0D-1) GO TO 630
   IF (J .LE. MAXARC*NLP) GO TO 610
    CALL FRAME
    HAS = 49
   CALL YSCALE(SNY, VORD, NDES, XKL, MAXARC, J)
   CALL PAXES(STEP, XMTR, VORD, NDES, LTITLE)
   CALL PLOTCS(STEP(2), 1.05*VORD, 'SENSITIVITY IN POLAR ANGLE', 26)
   CALL CTRORI(1.0)
   CALL POSITM(-1.75*XMTR, 0.325*VORD)
   IF (IUNITS .EQ. 1) CALL TYPECS('( RAD / HM )', 12)
   IF (IUNITS .EQ. 2) CALL TYPECS('( RAD / IN )', 12)
   CALL CTRORI(0.0)
610 MLP = (J - 1) / MAXARC + 1
   NAR = J - (MLP - 1) * MAXARC
   HAS = HAS + 1
   DO 620 I = 1, NDES
   VAR(I) = SNY(I,J)
   620 CONTINUE
   CALL THICK(1)
   CALL CTRSET(4)
   CALL PTPTLOT(STEP, VAR, 1, NDES, HAS)
   CALL THICK(2)
   CALL NSCURV(STEP, VAR, 1, NDES)
   CALL SYMKEY(STEP, VORD, XMTR, NDES, NAR, MLP, HAS, 11)
Listing of PSODPLOTS at 17:26:38 on JUL 23y 1982 for CCid=MCBB

630 CONTINUE
C
755     YORD = 0.0
756     DO 640 I = 1, NDES
757     IF (SNOLY(I) .GE. YORD) YORD = SNOLY(I)
758     IF (SNORLY(I) .GE. YORD) YORD = SNORLY(I)
761  640 CONTINUE
762     IF (YORD .LT. 1.0D-9) GO TO 660
763     VORD = 1.1 * YORD
764     CALL PAXES(STEP, XMTR, VORD, NDES, LTITLE)
765     CALL PLOTCS(STEP(2), 1.05*VORD, "SENSITIVITY IN POLAR ANGLE", 26)
766     CALL CTRORI(1.0)
767     CALL POSITN(-1.75*XHTR, 0.325*VORD)
768     IF (IUNITS .EQ. 1) CALL TYPECS("( RAD / MM )", 12)
769     IF (IUNITS .EQ. 2) CALL TYPECS("( RAD / IN )", 12)
770     CALL CTRORI(0.0)
771     IF (SNOLY(1) .LT. - 5.0D-1) GO TO 650
772     CALL CTRSET(4)
773     CALL THICK(1)
774     CALL PTPLOT(STEP, SNOLY, 1, NDES, 51)
775     CALL THICK(2)
776     CALL NSCURV(STEP, SNOLY, 1, NDES)
777     CALL SYMBKY(STEP, VORD, XMTR, NDES, 25, 11, 51)
778  650 IF (SNOLY(1) .LT. - 5.0D-1) GO TO 660
779     CALL THICK(1)
780     CALL CTRSET(4)
781     CALL PTPLOT(STEP, SNOLY, 1, NDES, 52)
782     CALL THICK(2)
783     CALL NSCURV(STEP, SNOLY, 1, NDES)
784     CALL SYMBKY(STEP, VORD, XMTR, NDES, 17, 11, 52)
785     MLP = 0
786     DO 690 J = 1, KKL
787        IF (J .EQ. MAXARC*NLP + 1) NGG = 0
788        IF (SNGY(J,J) .LT. - 5.0D-1) GO TO 690
789        NGG = NGG + 1
790        IF (J .LE. MAXARC*NLP .AND. NGG .NE. 1) GO TO 670
791     CALL FRAME
792     HAS = 49
793     CALL YSCALE(SNGY, VORD, NDES, KKL, MAXARC, J)
794     CALL PAXES(STEP, XMTR, VORD, NDES, LTITLE)
795     CALL PLOTCS(STEP(2), 1.05*VORD, "SENSITIVITY IN POLAR ANGLE", 26)
796     CALL CTRORI(1.0)
797     CALL POSITN(-1.75*XHTR, 0.325*VORD)
798     CALL TYPECS("( RAD / RAD )", 13)
799     CALL CTRORI(0.0)
800  670 MLP = (J - 1) / MAXARC + 1
801     NAR = J - (NLP - 1) * MAXARC
802     HAS = HAS + 1
803     DO 680 I = 1, NDES
804        VAR(I) = SNGY(I,J)
805     680 CONTINUE
806     CALL THICK(1)
807     CALL CTRSET(4)
808     CALL PTPLOT(STEP, VAR, 1, NDES, HAS)
809     CALL THICK(2)
810     CALL NSCURV(STEP, VAR, 1, NDES)
CALL SYMKEY(STEP, VORD, XMTR, NDES, NW, MLP, NAS, 17)
690 CONTINUE
C
YORD = 0.0
DO 700 I = -1, -NDES
IF (SNORY(I) .GT. YORD) YORD = SNORY(I)
IF (SNOSY(I) .GT. YORD) YORD = SNOSY(I)
IF (SNCRY(I) .GT. YORD) YORD = SNCRY(I)
700 CONTINUE
VORD = 1.1 * YORD
CALL FRAME
CALL PAXES(STEP, XMTR, VORD, NDES, LTITLE)
CALL PLOTCS(STEP(2), 1.05*VORD, "SENSITIVITY IN POLAR ANGLE", 26)
CALL CTORII(1.0)
CALL POSITN(-1.75*XMTR, 0.325*VORD)
CALL TYPECS("( RAD / RAD )", 13)
CALL CTORII(0.0)
IF (SNOSY(I) .LT. -5.0D-1) GO TO 710
CALL THICK(1)
CALL CTRSET(4)
CALL PTPLLOT(STEP, SNONY, 1, NDES, 51)
CALL THICK(2)
CALL NSCURV(STEP, SNOSY, 1, NDES)
CALL SYMBKY(STEP, VORD, XMTR, NDES, 25, 17, 51)
710 IF (SNOSY(I) .LT. -5.0D-1) GO TO 720
CALL THICK(1)
CALL CTRSET(4)
CALL PTPLLOT(STEP, SNOSY, 1, NDES, 52)
CALL THICK(2)
CALL NSCURV(STEP, SNOSY, 1, NDES)
CALL SYMBKY(STEP, VORD, XMTR, NDES, 17, 17, 52)
720 CALL THICK(1)
CALL CTRSET(4)
CALL PTPLLOT(STEP, SNCRY, 1, NDES, 53)
CALL THICK(2)
CALL NSCURV(STEP, SNCRY, 1, NDES)
CALL SYMBKY(STEP, VORD, XMTR, NDES, 13, 17, 53)
GO TO 810
C
730 CALL SETPLS(STEP, XMTR, NDES, VSCALS, IUNITS, MOTN, NORT, LTITLE)
C
CALL CTRSET(2)
CALL BROKEN(5, 10, 5, 10)
CALL POSIT(N(STEP(1), ADEV)
CALL JOIN(STEP(NDES), ADEV)
CALL POSITN(STEP(1), ADEV)
CALL JOIN(STEP(NDES), -ADEV)
CALL FULL
CALL CTRSET(4)
CALL THICK(1)
CALL PTPLLOT(STEP, ERPS, 1, NDES, 54)
CALL THICK(3)
CALL NSCURV(STEP, ERPS, 1, NDES)
CALL THICK(1)
CALL PTPLLOT(STEP, ERNS, 1, NDES, 54)
CALL THICK(3)
CALL NSCURV(STEP, ERNS, 1, NDES)
Listing of PSODPLOTS at 17:26:38 on JUL 23 1982 for CCid=NCBG

C
NLP = 0
DO 760 J = 1, KKL
IF (SNX(I,J) .LT. - 5.0D-1) GO TO 760
IF (J .LE. MAXARC*NLP) GO TO 740
CALL FRAME
MAS = 49
CALL YSCALE(SNX, VORD, NDES, KKL, MAXARC, J)
CALL PAXES(STEP, XMTR, VORD, NDES, LTITLE)
CALL CTRORI(1.0)
CALL POSIZ(-1.75*XMTR, 0.325*VORD)
IF (IUNITS .EQ. 1) CALL TYPESC(‘( MM / MM )’, 11)
IF (IUNITS .EQ. 2) CALL TYPESC(‘( IN / IN )’, 11)
CALL CTRORI(0.0)
NLP = (J - 1) / MAXARC + 1
NAR = J - (NLP - 1) * MAXARC
MAS = MAS + 1
DO 750 I = 1, NDES
VAR(I) = SNX(I,J)
750 CONTINUE
CALL THICK(2)
CALL NSCURV(STEP, VAR, 1, NDES)
CALL‘SYNKEY(STEP, VORD, XMTR, NDES, NAR, NLP, MAS, 11)
760 CONTINUE

C
NLP = 0
DO 790 J = 1, KKL
IF (J .EQ. MAXARC*NLP + 1) NGS = 0
IF (SNX(I,J) .LT. - 5.0D-1) GO TO 790
NGS = NGS + 1
IF (J .LE. MAXARC*NLP .AND. NGS .NE. 1) GO TO 770
CALL FRAME
MAS = 49
CALL YSCALE(SNGX, VORD, NDES, KKL, MAXARC, J)
CALL PAXES(STEP, VAR, 1, NDES, MAS)
CALL THICK(2)
CALL NSCURV(STEP, VAR, 1, NDES)
CALL‘SYNKEY(STEP, VORD, XMTR, NDES, NAR, NLP, MAS, 11)
770 CONTINUE

C
VORD = 0.0
Listing of PSODPLOTs at 17:26:38 on JUL 23, 1982 for CCid=NCB8

```
929    DO 800 I = 1, NDES
930        IF (SNCRX(I) .GT. YORD) YORD = SNCRX(I)
931 800 CONTINUE
932    VORD = 1.1 * YORD
933    CALL FRAME
934    CALL PAXES(STEP, XNTR, YORD, NDES, LTITLE)
935    CALL CTRORI(1.0) --
936    CALL POSITN(-1.75*XNTR, 0.325*YORD)
937    IF (IUNITS .EQ. 1) CALL TYPECS((' MM / RAD '), 12)
938    IF (IUNITS .EQ. 2) CALL TYPECS((' IN / RAD '), 12)
939    CALL CTRORI(0.0)
940    CALL THICK(1)
941    CALL CIRSET(4)
942    CALL PPT]OT(STEP, SNCRX, 1, NDES, 51)
943    CALL THICK(2)
944    CALL NSCURV(STEP, SNCRX, 1, NDES)
945    CALL SYMBKY(STEP, VORD, XNTR, NDES, 13, 17, 51)
946    C
947    C
948    810 CALL CIRSET(1)
949    CALL THICK(1)
950    CALL GREEN
951    STOP
952    END
953        C
954        C * * **** * * * * * * * * * * * * * * * *
955        C
956    SUBROUTINE SETPLS(STEP, XNTR, NDES, VSCALE, IUNITS, MOTH, NORT,
957                           LTITLE)
958        C
959        IMPLICIT LOGICAL*1(L)
960        DIMENSION LTITLE(72)
961        REAL STEP(NDES)
962        C
963        CALL CTRSET(1)
964        CALL PSSPACE(0.2, 0.85, 0.15, 0.75)
965        CALL WINDOW(STEP(1), STEP(NDES), -VSCALE, VSCALE)
966        CALL MAP(STEP(1), STEP(NDES), -VSCALE, VSCALE)
967        CALL BORDER
968        CALL THICK(2)
969        CALL PLOTCS(STEP(1), 1.2*VSCALE, LTITLE, 72)
970        CALL CIRSET(2)
971        CALL AXES
972        CALL PLOTCS(STEP(1) + 2.0*XNTR, -0.15*VSCALE, 'INPUT POSITION',
973                           1)
974        CALL TYPECS((' DEGREES '), 10)
975        CALL CTRORI(1.0)
976        CALL PLOTCS(STEP(1) - 1.5*XNTR, -0.8*VSCALE, 'OUTPUT DEVIATION',
977                           1)
978        GO TO (10, 20, 30, 10), MOTH
979 10 IF (IUNITS .EQ. 1) CALL TYPECS((' MILLIMETERS '), 14)
980    IF (IUNITS .EQ. 2) CALL TYPECS((' INCHES '), 11)
981    GO TO 40
982 20 CALL TYPECS((' DEGREES '), 12)
983    GO TO 40
984 30 IF (NORT .EQ. 1) GO TO 10
985    GO TO 20
```

Listing of P50PLOTS at 17:26:38 on JUL 23, 1982 for CCid=MCBB

987 40 CALL CTRORI(0.0)
988 CALL WINDOW(STEP(1), STEP(NDES), -1.2*VSCALE, VSCALE)
989 CALL POSITH(STEP(1) + 0.5*XNTR, -1.2*VSCALE)
990 CALL BROKEN(5, 10, 5, 10)
991 CALL JOIN(STEP(1) * 1.5*XNTR, -1.2*VSCALE)
992 CALL TYPECS(" MAX. ALLOWABLE OUTPUT DEVIATION", 32)
993 CALL FULL
994 CALL THICK(2)
995 C
996 RETURN
997 END
998 C
999 C
1000 C
1001 C
1002 C
1003 C
1004 C
1005 C
1006 C
1007 C
1008 C
1009 C
1010 C
1011 C
1012 C
1013 C
1014 C
1015 C
1016 C
1017 C
1018 C
1019 C
1020 C
1021 C
1022 C
1023 C
1024 C
1025 C
1026 C
1027 C
1028 C
1029 C
1030 C
1031 C
1032 C
1033 C
1034 C
1035 C
1036 C
1037 C
1038 C
1039 C
1040 C
1041 C
1042 C
1043 C
1044 C

SUBROUTINE PAXES(STEP, XMTR, VORD, NDES, LTITLE)

IMPLICIT LOGICAL(1)

DIMENSION STEP(NDES), LTITLE(72)

CALL CTRSET(1)
CALL THICK(1)
CALL PSPACE(0.20, 0.80, 0.20, 0.80)
CALL WINDOW(STEP(1), STEP(NDES), 0.0, VORD)
CALL MAP(STEP(1), STEP(NDES), 0.0, VORD)
CALL BORDER
CALL THICK(2)
CALL PLOTCS(STEP(1), 1.1*VORD, LTITLE, 72)
CALL CTRSET(2)
CALL UNDLIM(1)
CALL PLOTCS(STEP(NDES) + XMTR, VORD, "KEY 1-", 6)
CALL UNDLIN(0)
CALL AXES
CALL PLOTCS(1.5*XNTR, -0.1*VORD, "INPUT POSITION ( DEGREES )", 26)
CALL CTRORI(1.0)
CALL PLOTCS(-2.75*XNTR, 0.25*VORD, "OUTPUT SENSITIVITY", 18)
CALL PLOTCS(-2.25*XNTR, 0.2*VCRD, "TO PARAMETER DEVIATION", 22)
CALL CTRORI(0.0)

RETURN
END

SUBROUTINE YSCALE(SHUt VORD, NDS, KKL, MXR, NUM)

DIMENSION SHU(37,100)

LK = NUM / MXR
MAM = (LK + 1) * MXR
SMX = 0.0
DO 10 J = NUM, MAM
DO 10 I = 1, NDS
IF (SHU(I,J) .GT. SMX) SMX = SHU(I,J)
10 CONTINUE

VORD = 1.1 * SMX
RETURN
END
SUBROUTINE SYMKY(STEP, VORD, XMTR, NDES, NR, NL, NS, NC)

DIMENSION STEP(NDES)

PM = FLOAT(NS - 49)
PS = VORD - 0.125 * PM * VORD
RS = STEP(NDES) + 1.5 * XMTR
CALL CTRSET(4)
CALL THICK(1)
CALL PLOTHC(Rs, PS, NS)
CALL HSPACE(5)
CALL THICK(2)
IF (NC .EQ. 11) CALL CTRSET(2)
CALL TYPENC(NC)
CALL SUFFIX
CALL TYPENI(NR)
CALL TYPENI(38)
CALL TYPENI(NL)
CALL CTRSET(2)
CALL NORMAL
RETURN
END

SUBROUTINE SYMKY(STEP, VORD, XMTR, NDES, MS, NC, MS)

DIMENSION STEP(NDES)

PM = FLOAT(NS - 50)
PS = VORD - 0.125 * PM * VORD
RS = STEP(NDES) + 1.5 * XMTR
CALL CTRSET(4)
CALL THICK(1)
CALL PLOTHC(Rs, PS, NS)
CALL HSPACE(5)
CALL THICK(2)
IF (NC .EQ. 11) CALL CTRSET(2)
CALL TYPENC(NC)
CALL SUFFIX
CALL TYPENI(NS)
CALL NORMAL
RETURN
END
APPENDIX IIA

KINEMATIC ANALYSIS OF A FOUR-BAR LINKAGE
IIA.1 DISPLACEMENTS

With reference to Fig. 8.4, the vector equation for the polygon with arcs \(a_1, a_2, a_3\) and \(a_4\) may be expressed as

\[a_1 e^{i\theta_1} + a_2 e^{i\theta_2} - a_3 e^{i\theta_3} - a_4 e^{i\theta_4} = 0\]  

IIA.1

Expanding and separating the real and imaginary parts gives

\[a_1 \cos \theta_1 + a_2 \cos \theta_2 - a_3 \cos \theta_3 - a_4 \cos \theta_4 = 0\]  

IIA.2

\[a_1 \sin \theta_1 + a_2 \sin \theta_2 - a_3 \sin \theta_3 - a_4 \sin \theta_4 = 0\]  

IIA.2

Eliminating \(\theta_2\) gives

\[R_1 \sin \theta_3 + R_2 \cos \theta_3 - R_3 = 0\]  

IIA.3

where

\[R_1 = \sin \theta_1 - \frac{a_4}{a_1} \sin \theta_4\]

\[R_2 = \cos \theta_1 - \frac{a_4}{a_1} \cos \theta_4\]

\[R_3 = \frac{a_1^2 - a_2^2 + a_3^2 + a_4^2}{2a_1a_3} - \frac{a_1}{a_3} \cos (\theta_1 - \theta_4)\]

Substituting for \(\sin \theta_3\) and \(\cos \theta_3\) in terms of \(\tan \frac{\theta_3}{2}\) and rearranging gives

\[(R_2 + R_3) \tan^2 \frac{\theta_3}{2} - 2 R_1 \tan \frac{\theta_3}{2} - (R_2 - R_3) = 0\]  

IIA.4
Hence

\[ \tan \frac{\theta_3}{2} = \frac{R_1 \pm \sqrt{R_1^2 + R_2^2 - R_3^2}}{R_2 + R_3} \]  

IIA.5

The configuration shown in Fig. 8.4 corresponds to the negative square root,

\[ \theta_3 = 2 \tan^{-1} \frac{R_1 - \sqrt{R_1^2 + R_2^2 - R_3^2}}{R_2 + R_3} \]  

IIA.6

Substituting in IIA.2 and rearranging gives

\[ \theta_2 = \tan^{-1} \frac{-a_1 \sin \theta_1 + a_3 \sin \theta_3 + a_4 \sin \theta_4}{-a_1 \cos \theta_1 + a_3 \cos \theta_3 + a_4 \cos \theta_4} \]  

IIA.7

IIA.2 VELOCITIES

Differentiating IIA.1 w.r.t. time gives

\[ a_1 \dot{\theta}_1 e^{i\theta_1} + a_2 \dot{\theta}_2 e^{i\theta_2} - a_3 \theta_3 e^{i\theta_3} = 0 \]  

IIA.8

Rewriting in component form

\[ a_1 \dot{\theta}_1 \cos \theta_1 + a_2 \dot{\theta}_2 \cos \theta_2 - a_3 \theta_3 \cos \theta_3 = 0 \]  

IIA.9

\[ a_1 \dot{\theta}_1 \sin \theta_1 + a_2 \dot{\theta}_2 \sin \theta_2 - a_3 \theta_3 \sin \theta_3 = 0 \]
Eliminating $\dot{\theta}_2$ gives after rearranging

$$\dot{\theta}_3 = \frac{a_1 \sin(\theta_2 - \theta_1)}{a_3 \sin(\theta_2 - \theta_3)} \dot{\theta}_1$$  \hspace{1cm} \text{IIA.10}$$

Eliminating $\dot{\theta}_3$ from equations IIA.9 and rearranging gives

$$\dot{\theta}_2 = \frac{a_1 \sin(\theta_3 - \theta_1)}{a_2 \sin(\theta_2 - \theta_3)} \dot{\theta}_1$$  \hspace{1cm} \text{IIA.11}$$

IIA.3 ACCELERATIONS

Differentiating IIA.10 with respect to time gives

$$\ddot{\theta}_3 = \frac{a_1 \cos(\theta_2 - \theta_1)}{a_3 \sin(\theta_2 - \theta_3)} \left[ \ddot{\theta}_2 - \dot{\theta}_1 \right] \dot{\theta}_1 - \frac{a_1 \sin(\theta_2 - \theta_1) \cos(\theta_2 - \theta_3)}{a_3 \sin^2(\theta_2 - \theta_3)} \left[ \ddot{\theta}_2 - \ddot{\theta}_3 \right] \dot{\theta}_1 + \frac{a_1 \sin(\theta_2 - \theta_1)}{a_3 \sin(\theta_2 - \theta_3)} \ddot{\theta}_1$$

Substituting from IIA.10 and IIA.11 then for $\dot{\theta}_1 = \text{constant}$

$$\ddot{\theta}_3 = \dot{\theta}_3 \left[ \frac{\ddot{\theta}_2 - \dot{\theta}_1}{\tan(\theta_2 - \theta_1)} - \frac{\ddot{\theta}_2 - \ddot{\theta}_3}{\tan(\theta_2 - \theta_3)} \right]$$  \hspace{1cm} \text{IIA.12}$$
Differentiating IIA.11 and substituting as above gives

\[ \ddot{\theta}_2 = \dot{\theta}_2 \left[ \frac{\dot{\theta}_3 - \dot{\theta}_1}{\tan(\theta_3 - \theta_1)} - \frac{\dot{\theta}_2 - \dot{\theta}_3}{\tan(\theta_2 - \theta_3)} \right] \]  

IIA.13

IIA.4 MOTION OF MASS CENTRES

IIA.4.1 Displacements

Link 1: Crank

\[ x_1 = \rho_1 \cos(\theta_1 + \lambda_1) \]
\[ y_1 = \rho_1 \sin(\theta_1 + \lambda_1) \]

Link 2: Coupler

\[ x_2 = a_1 \cos \theta_1 + \rho_2 \cos(\theta_2 + \lambda_2) \]
\[ y_2 = a_1 \sin \theta_1 + \rho_2 \sin(\theta_2 + \lambda_2) \]

Link 3: Follower

\[ x_3 = \rho_3 \cos(\theta_3 + \lambda_3) \]
\[ y_3 = \rho_3 \sin(\theta_3 + \lambda_3) \]

IIA.14

IIA.4.2 Velocities

Differentiating equations IIA.14 and substituting for \( \dot{\theta}_2 \) and \( \dot{\theta}_3 \) where applicable gives:

\[ \dot{x}_1 = -\rho_1 \dot{\theta}_1 \sin(\theta_1 + \lambda_1) \]
\[ \dot{y}_1 = \rho_1 \dot{\theta}_1 \cos(\theta_1 + \lambda_1) \]

IIA.15
\[ \begin{align*}
\dot{x}_2 &= -a_1 \dot{\theta}_1 \sin \theta_1 - \frac{\rho_2 a_1 \dot{\theta}_1 \sin(\theta_3 - \theta_1)}{a_2 \sin(\theta_2 - \theta_3)} \sin(\theta_2 + \lambda_2) \\
\dot{y}_2 &= a_1 \dot{\theta}_1 \cos \theta_1 + \frac{\rho_2 a_1 \dot{\theta}_1 \sin(\theta_3 - \theta_1)}{a_2 \sin(\theta_2 - \theta_3)} \cos(\theta_2 + \lambda_2) \\
\dot{x}_3 &= -\rho_3 \dot{\theta}_1 \frac{a_1 \sin(\theta_2 - \theta_1)}{a_3 \sin(\theta_2 - \theta_3)} \sin(\theta_3 + \lambda_3) \\
\dot{y}_3 &= \rho_3 \dot{\theta}_1 \frac{a_1 \sin(\theta_2 - \theta_1)}{a_3 \sin(\theta_2 - \theta_3)} \cos(\theta_3 + \lambda_3)
\end{align*} \]

IIA.15

IIA.4.3 Accelerations

Differentiating equations IIA.14 twice gives

\[ \begin{align*}
\ddot{x}_1 &= -\rho_1 \ddot{\theta}_1 \cos(\theta_1 + \lambda_1) \\
\ddot{y}_1 &= -\rho_1 \ddot{\theta}_1 \sin(\theta_1 + \lambda_1) \\
\ddot{x}_2 &= -a_1 \dot{\theta}_1 \cos \theta_1 - \rho_2 \dot{\theta}_2 \cos(\theta_2 + \lambda_2) - \rho_2 \dot{\theta}_2 \sin(\theta_2 + \lambda_2) \\
\ddot{y}_2 &= -a_1 \dot{\theta}_1 \sin \theta_1 - \rho_2 \dot{\theta}_2 \sin(\theta_2 + \lambda_2) + \rho_2 \dot{\theta}_2 \cos(\theta_2 + \lambda_2) \\
\ddot{x}_3 &= -\rho_3 \dot{\theta}_3 \cos(\theta_3 + \lambda_3) - \rho_3 \dot{\theta}_3 \sin(\theta_3 + \lambda_3) \\
\ddot{y}_3 &= -\rho_3 \dot{\theta}_3 \sin(\theta_3 + \lambda_3) + \rho_3 \dot{\theta}_3 \cos(\theta_3 + \lambda_3)
\end{align*} \]

IIA.16
APPENDIX IIIB

DYNAMIC ANALYSIS OF A FOUR-BAR LINKAGE
IIB.1 TERMINOLOGY - Refer to Fig. 8.5

\( a_i \) = vector connecting the joints on link \( i \) - i.e. arc lengths

\( \rho_i, \lambda_i \) = polar coordinates (radius and angle respectively) defining mass centre position of link \( i \), relative to local origin and arc length vector.

\( I_i \) = second moment of mass of link \( i \) about local origin.

\( F_{ij}, F_{ij} \) = cartesian components along the \( x \)- and \( y \)-direction respectively of the joint force exerted by link \( i \) on \( j \).

\( F_{ei}, M_{ei} \) = Resultant external force and moment respectively acting on link \( i \)

\( \theta_i \) = angular orientation of link \( i \) relative to the \( x \)-direction.

\( \rho'_i, \lambda'_i \) = polar coordinates of mass centre from the other joint on the link as seen on Fig. 8.5

IIB.2 EQUATIONS OF MOTION

With reference to the free body diagrams in Fig. 8.5, the following equations of motion (force equations along the cartesian coordinates and moment equation about the centre of
of mass) may be written for the respective moving links.

Link 1

\[ F_{e1_x} + F_{21_x} + F_{41_x} = m_1 \ddot{x}_1 \]

\[ F_{e1_y} + F_{21_y} + F_{41_y} = m_1 \ddot{y}_1 \]

\[ F_{41_x} \rho_1 \sin(\theta_1 + \lambda_1) - F_{41_y} \rho_1 \cos(\theta_1 + \lambda_1) - F_{21_x} \rho_1 \sin(\theta_1 - \lambda_1) \]

\[ + F_{21_y} \rho_1 \cos(\theta_1 - \lambda_1) + M_{e1} = (I_1 - m_1 \rho_1^2) \ddot{\theta}_1 \]

Link 2

\[ F_{e2_x} + F_{12_x} + F_{32_x} = m_2 \ddot{x}_2 \]

\[ F_{e2_y} + F_{12_y} + F_{32_y} = m_2 \ddot{y}_2 \]

\[ F_{12_x} \rho_2 \sin(\theta_2 + \lambda_2) - F_{12_y} \rho_2 \cos(\theta_2 + \lambda_2) - F_{32_x} \rho_2 \sin(\theta_2 - \lambda_2) \]

\[ + F_{32_y} \rho_2 \cos(\theta_2 - \lambda_2) + M_{e2} = (I_2 - m_2 \rho_2^2) \ddot{\theta}_2 \]

Link 3

\[ F_{e3_x} + F_{23_x} + F_{43_x} = m_3 \ddot{x}_3 \]

\[ F_{e3_y} + F_{23_y} + F_{43_y} = m_3 \ddot{y}_3 \]

\[ F_{43_x} \rho_3 \sin(\theta_3 + \lambda_3) - F_{43_y} \rho_3 \cos(\theta_3 + \lambda_3) - F_{23_x} \rho_3 \sin(\theta_3 - \lambda_3) \]

\[ + F_{23_y} \rho_3 \cos(\theta_3 - \lambda_3) + M_{e3} = (I_3 - m_3 \rho_3^2) \ddot{\theta}_3 \]
IIB. 3 JOINT FORCES

Note the joint forces $F_{ij}$ and $F_{ji}$ are equal and opposite, i.e. $F_{ij} = -F_{ji}$. Hence substituting for $F_{12x}$ and $F_{12y}$ from the force equations into the moment equation of set IIB.2 gives:

$$F_{23x} \left[ \rho_2 \sin(\theta_2 + \lambda_2) + \rho_2' \sin(\theta_2 - \lambda_2') \right]$$

$$-F_{23y} \left[ \rho_2 \cos(\theta_2 + \lambda_2) + \rho_2' \cos(\theta_2 - \lambda_2') \right]$$

$$-F_{e2x} \rho_2 \sin(\theta_2 + \lambda_2) + F_{e2y} \rho_2 \cos(\theta_2 + \lambda_2) + M_{ez}$$

$$= (I_2 - m_2 \rho_2^2) \ddot{\theta}_2 - m_2 \rho_2 \left[ \ddot{x}_2 \sin(\theta_2 + \lambda_2) - \ddot{y}_2 \cos(\theta_2 + \lambda_2) \right]$$

IIB. 4

Note, with reference to Fig. 8.5, that

$$\rho_2 \sin(\theta_2 + \lambda_2) + \rho_2' \sin(\theta_2 - \lambda_2') = a_2 \sin \theta_2$$

and

$$\rho_2 \cos(\theta_2 + \lambda_2) + \rho_2' \cos(\theta_2 - \lambda_2') = a_2 \cos \theta_2$$

and from Appendix IIA.

$$\ddot{x}_2 \sin(\theta_2 + \lambda_2) - \ddot{y}_2 \cos(\theta_2 + \lambda_2)$$

$$= -a_1 \dot{\theta}_1^2 \sin(\theta_2 + \lambda_2 - \theta_1) - \rho_2 \ddot{\theta}_2$$
Substituting in IIB.4 gives

\[
F_{23x} a_2 \sin \theta_2 - F_{23y} a_2 \cos \theta_2 - F_{e2x} \rho_2 \sin(\theta_2 + \lambda_2)
\]

\[
+ F_{e2y} \rho_2 \cos(\theta_2 + \lambda_2) + M_{e2}
\]

\[
= I_2 \ddot{\theta}_2 + m_2 \rho_2 a_1 \dot{\theta}_1^2 \sin(\theta_2 + \lambda_2 - \theta_1)
\]

IIB.5

Similarly the set of equation IIB.3 gives

\[
-F_{23x} a_3 \sin \theta_3 + F_{23y} a_3 \cos \theta_3 - F_{e3x} \rho_3 \sin(\theta_3 + \lambda_3)
\]

\[
+ F_{e3y} \rho_3 \cos(\theta_3 + \lambda_3) + M_{e3}
\]

\[
= I_3 \ddot{\theta}_3
\]

IIB.6

Let

\[
P = I_2 \ddot{\theta}_2 + m_2 \rho_2 a_1 \dot{\theta}_1^2 \sin(\theta_2 + \lambda_2 - \theta_1)
\]

\[
Q = I_3 \ddot{\theta}_3
\]

If the external forces and moments are zero or negligible then equations IIB.5, IIB.6 become
\[
F_{23x} a_2 \sin \theta_2 - F_{23y} a_2 \cos \theta_2 = P
\]
\[
-F_{23x} a_3 \sin \theta_3 + F_{23y} a_3 \cos \theta_3 = Q
\]

Solving these two equations simultaneously gives

\[
F_{23x} = \frac{P \cos \theta_3}{a_2 \sin \mu} + \frac{Q \cos \theta_2}{a_3 \sin \mu} \quad \text{IIB.7}
\]
\[
F_{23y} = \frac{P \sin \theta_3}{a_3 \sin \mu} + \frac{Q \sin \theta_2}{a_3 \sin \mu}
\]

where \( \mu = \theta_2 - \theta_3 \)

Hence

\[
F_{43x} = m_3 \ddot{x}_3 - F_{23x} \quad \text{IIB.8}
\]
\[
F_{43y} = m_3 \ddot{y}_3 - F_{23y}
\]
\[
F_{12x} = m_2 \ddot{x}_2 + F_{23x} \quad \text{IIB.9}
\]
\[
F_{12y} = m_2 \ddot{y}_2 + F_{23y}
\]
\[
F_{41x} = m_1 \ddot{x}_1 + m_2 \ddot{x}_2 + F_{23x} \quad \text{IIB.10}
\]
\[
F_{41y} = m_1 \ddot{y}_1 + m_2 \ddot{y}_2 + F_{23y}
\]
Substituting for \( \ddot{x}_i \) and \( \ddot{y}_i \) from Appendix IIA

\[
F_{43_x} = -m_3 \rho_3 \left( \dot{\theta}_3 \cos(\theta_3 + \lambda_3) + \ddot{\theta}_3 \sin(\theta_3 + \lambda_3) \right) - F_{23_x}
\]

\[
F_{43_y} = -m_3 \rho_3 \left( \dot{\theta}_3 \sin(\theta_3 + \lambda_3) - \ddot{\theta}_3 \cos(\theta_3 + \lambda_3) \right) - F_{23_x}
\]

IIB.11

\[
F_{12_x} = -m_2 \left( a_1 \dot{\theta}_1 \cos \theta_1 + \rho_2 \left[ \dot{\theta}_2 \cos(\theta_2 + \lambda_2) + \ddot{\theta}_2 \sin(\theta_2 + \lambda_2) \right] \right) + F_{23_x}
\]

\[
F_{12_y} = -m_2 \left( a_1 \dot{\theta}_1 \sin \theta_1 + \rho_2 \left[ \dot{\theta}_2 \sin(\theta_2 + \lambda_2) - \ddot{\theta}_2 \cos(\theta_2 + \lambda_2) \right] \right) + F_{23_y}
\]

IIB.12

\[
F_{41_x} = -m_1 \rho_1 \dot{\theta}_1 \cos(\theta_1 + \lambda_1) + F_{12_x}
\]

IIB.13

\[
F_{41_y} = -m_1 \rho_1 \dot{\theta}_1 \sin(\theta_1 + \lambda_1) + F_{12_y}
\]

The resultant joint force is given by

\[
F_{ij} = \sqrt{F_{ij_x}^2 + F_{ij_y}^2}
\]

IIB.14

i and j taking the respective values above.

The forces are represented by their vector components in Fig. 8.2.
APPENDIX IIC

LISTING OF COMPUTER PROGRAM

CONTACT
Listing of CONTACT at 16:17:27 on JUL 23, 1982 for CCid=MCBB

** PROGRAM FOR OPTIMIZING MASS DISTRIBUTION TO MAINTAIN CONTACT IN THE JOINTS OF FOUR-BAR LINKAGE MECHANISMS **

**

IMPLICIT REAL*8(A-H,O-Z)

DIMENSION X(15), G(15), U(135), BL(15), BU(15), DELTA(15), HESD(15), HESL(105)

INTEGER IU(2), ISTATE(15), ITITLE(18)

LOGICAL LOCSCH

COMMON ARC1, ARC2, ARC3, ARC4, CTA4, CTA1D, PI, AMAS01, AMAS02, AMAS03, RR01, RR02, RR03, ALMD01, ALMD02, ALMD03, AI01, AI02, AI03, M

EXTERNAL E04JBQ, FUNCT, MONIT

CALL FTNCMDVASSIGN 7=JOINT(*L+1); ')

CALL TIME(0)

PI=4.0D0*0ATAN(1.0D0)

DEGRAD=PI/180.0D0

N=15

LIW=2

LW=135

IPRINT=1000

MAXCAL=40*N*(N+5)

ETA=5.00-01

XTOL=1.0D-03

STEPNX=5.0D+00

READ(5,1005) ITITLE

READ(5,1010) ARC1, ARC2, ARC3, ARC4, CTA4, CTA1D, M

READ(5,1015) AMAS01, RR01, ALMD01, AI01, AMAS02, RR02, ALMD02, AI02, AMAS03, RR03, ALMD03, AI03

READ(5,1015) (X(I), I=1,15)

WRITE(6,1110)

WRITE(6,1005) ITITLE

------CHANGE LENGTHS FROM MILLIMETERS TO METERS

CTOM=1.0D-3

ARC1=ARC1*CTOM

ARC2=ARC2*CTOM

ARC3=ARC3*CTOM

ARC4=ARC4*CTOM

RR01=RR01*CTOM

RR02=RR02*CTOM

RR03=RR03*CTOM

X(2)=X(2)*CTOM

X(5)=X(5)*CTOM

X(7)=X(7)*CTOM
Listing of CONTACT at 16:17:27 on JUL 23, 1982 for CCid=MCBB

59  X(9) = X(9) * CTOM
60  X(11) = X(11) * CTOM
61  BL(2) = BL(2) * CTOM
62  BU(2) = BU(2) * CTOM
63  BL(5) = BL(5) * CTOM
64  BU(5) = BU(5) * CTOM
65  BL(7) = BL(7) * CTOM
66  BU(7) = BU(7) * CTOM
67  BL(9) = BL(9) * CTOM
68  BU(9) = BU(9) * CTOM
69  BL(11) = BL(11) * CTOM
70  BU(11) = BU(11) * CTOM

C
C-------CHANGE ANGLES FROM DEGREES TO RADIANS
C
72  CTA4 = CTA4 * DEGRAD
73  X(3) = X(3) * DEGRAD
74  X(6) = X(6) * DEGRAD
75  X(10) = X(10) * DEGRAD
76  X(12) = X(12) * DEGRAD
77  X(13) = X(13) * DEGRAD
78  X(14) = X(14) * DEGRAD
79  X(15) = X(15) * DEGRAD
80  BL(3) = BL(3) * DEGRAD
81  BU(3) = BU(3) * DEGRAD
82  BL(6) = BL(6) * DEGRAD
83  BU(6) = BU(6) * DEGRAD
84  BL(10) = BL(10) * DEGRAD
85  BU(10) = BU(10) * DEGRAD
86  BL(12) = BL(12) * DEGRAD
87  BU(12) = BU(12) * DEGRAD
88  BL(13) = BL(13) * DEGRAD
89  BU(13) = BU(13) * DEGRAD
90  BL(14) = BL(14) * DEGRAD
91  BU(14) = BU(14) * DEGRAD
92  BL(15) = BL(15) * DEGRAD
93  BU(15) = BU(15) * DEGRAD

94  DO 20 I = 1, N
95      MI = I - 1
96      FMI = DFLOAT(MI)
97      FMH = DFLOAT(M)
98      CTA1(I) = FMI * 2.0D0 * PI / FMH
99  CONTINUE
100  C
101  IFAIL = 1
102  CALL E04HBF(N,FUNCT,X,J,DELTA,HESL,LH,HESD,F,G,IW, *  
103     LIW,W,LU,IFAIL)
104  C
105  WRITE(6,1020) J
106  C
107  BIG = HESD(1)
108  SMALL = HESD(1)
109  C
110  DO 30 I = 2, N
111      IF(BIG .LT. HESD(I)) BIG = HESD(I)
112      IF(SMALL .GT. HESD(I)) SMALL = HESD(I)
113  CONTINUE
114
Listing of CONTACT at 16:17:27 on JUL 23, 1982 for CCid=MCBB

117    30 CONTINUE
118    C
119    IF(BIG .LT. 1.0D+6*SMALL)GOTO 35
120    C
121    WRITE(6,1030) (HESD(I),I=1,N)
122    GOTO 60
123    C
124    35 LOCSCH=.FALSE.
125    INTYPE=1
126    FEST=0.0D0
127    IBOUND=0
128    C
129    CALL E04JBF(N,FUNCT,MONIT,IPRINT,LOCSCH,INTYPE,E04JBO,
130    * MAXCAL,ETA,XTOL,STEPNX,FEST,DELTA,IBOUND,
131    * BL,BU,X,HESL,LH,HESD,ISTATE,F,G,IW,LW,
132    * U,LU,IFAIL)
133    C
134    .. TEST WHETHER IFAIL IS NON-ZERO ..
135    C
136    IF(IFAIL .NE. 0) WRITE(6,1040) IFAIL
137    IF(IFAIL .EQ. 1) GOTO 60
138    C
139    WRITE(6,1050) F
140    WRITE(6,1060) (F(J),J=1,N)
141    C
142    CALL FUNCT(I,N,X,F,G,IW,LW)
143    CALL RESULT(M,ITITLE)
144    C
145    IF(IFAIL .NE. 2) GOTO 60
146    C
147    WRITE(6,1070) (ISTATE(I),I=1,N)
148    WRITE(6,1080) (HESL(I),I=1,LH)
149    C
150    WRITE(6,1090) (HESD(I),I=1,N)
151    C
152    60 WRITE(6,1100)
153    CALL TIME(1,-1,TIM)
154    WRITE(6,1110)
155    STOP
156
157    1005 FORMAT(18A4), 1010 FORMAT(6F10.5,15)
158    1015 FORMAT(4F15.6)
159    1020 FORMAT(///1H ,13, 37H FUNCTION EVALUATIONS WERE NEEDED BY ,
160    * 6HE04HBF)
161    1030 FORMAT(///48H TRY RESCALING THE PROBLEM. ELEMENTS OF HESD ARE,
162    * 3(1P5E15.4))
163    1040 FORMAT(///16H ERROR EXIT TYPE, 13,23H - SEE ROUTINE DOCUMENT)
164    1050 FORMAT(1H1,27H FUNCTION VALUE ON EXIT IS , E15.6)
165    1060 FORMAT(13H AT THE POINT, 3(/5E15.6))
166    1070 FORMAT(2H WHERE ISTATE CONTAINS, 15I5, 1H,)
167    1080 FORMAT(14H HESL CONTAINS, 3(/1P5E20.4))
168    1090 FORMAT(14H AND HESD CONTAINS, 3(/1P5E20.4))
169    1100 FORMAT(///'EXECUTION TIME')
170    1110 FORMAT(1H1)
171    C
172    END
173
174    C
SUBROUTINE FUNCT(IFLAG, NC, FC, GC, IU, LIU, U, LU)

IMPLICIT REAL*B(A-H,P-Z)

DIMENSION XC(N), U(LU), GC(N), Z41SQ(360), Z12SQ(360),
* Z23SQ(360), Z43SQ(360), FZ12(360), FZ23(360),
* FZ43(360), FZ41(360)

INTEGER IU(LIU)

COMMON ARC1, ARC2, ARC3, ARC4, CTA4, CTA1(361), CTA0D, PI, AMASO1,
* AMASO2, AMASO3, RRO1, RRO2, RRO3, ALMDO1, ALMDO2,
* ALMDO3, AIO1, AIO2, AIO3, M

COMMON /RESLT/ AMASS1, RRS1, ALMDS1, AIS1, AMASS2, RRS2, ALMDS2, AIS2,
* AMASS3, RRS3, ALMDS3, AIS3, FI2X(360), FI2Y(360),
* F23X(360), F23Y(360), F43X(360), F43Y(360),
* F41X(360), F41Y(360), PID

PID = 8.0D+00 * DATAN(1.0D+00)
DNILA = 0.0D+00

AMASS1 = XC(1)
RRS1 = XC(2)

ALMDS1 = DMOD(XC(3), PID)
AIS1 = AMASS1 * RRS1**2

AMASS2 = XC(4)
RRS2 = XC(5)

ALMDS2 = DMOD(XC(6), PID)
AIS2 = (RRS2**2 + XC(7)**2) * AMASS2

AMASS3 = XC(8)
RRS3 = XC(9)

ALMDS3 = DMOD(XC(10), PID)
AIS3 = (RRS3**2 + XC(11)**2) * AMASS3

ZT12 = DMOD(XC(12), PID)
ZT23 = DMOD(XC(13), PID)
ZT43 = DMOD(XC(14), PID)
ZT41 = DMOD(XC(15), PID)

AMAS1 = AMASO1 + AMASS1
AMAS2 = AMASO2 + AMASS2
AMAS3 = AMASO3 + AMASS3

XP1 = (AMASO1 * RRO1 * DCOS(ALMDO1) + AMASS1 * RRS1 * DCOS(ALMDS1)) / AMAS1
YP1 = (AMASO1 * RRO1 * DSIN(ALMDO1) + AMASS1 * RRS1 * DSIN(ALMDS1)) / AMAS1

XP2 = (AMASO2 * RRO2 * DCOS(ALMDO2) + AMASS2 * RRS2 * DCOS(ALMDS2)) / AMAS2
YP2 = (AMASO2 * RRO2 * DSIN(ALMDO2) + AMASS2 * RRS2 * DSIN(ALMDS2)) / AMAS2

XP3 = (AMASO3 * RRO3 * DCOS(ALMDO3) + AMASS3 * RRS3 * DCOS(ALMDS3)) / AMAS3
YP3 = (AMASO3 * RRO3 * DSIN(ALMDO3) + AMASS3 * RRS3 * DSIN(ALMDS3)) / AMAS3

RR1 = DSORT(XP1**2 + YP1**2)
RR2 = DSORT(XP2**2 + YP2**2)
RK3 = DSORT(XP3**2 + YP3**2)

ALMD1 = DATAN2(YP1, XP1)
IF(ALMD1 .LT. DNILA) ALMD1 = ALMD1 + PID
Listing of CONTACT at 16:17:27 on JUL 23, 1982 for CCid=MCBB

ALMD2=DATAN2(YP2, XP2)
IF(ALMD2 .LT. DNIL) ALMD2=ALMD2+PID
ALMD3=DATAN2(YP3, XP3)
IF(ALMD3 .LT. DNIL) ALMD3=ALMD3+PID

C  A11=A101+A1S1
A12=A102+A1S2
A13=A103+A1S3

C  FUN = 0.0D+00

C  DO 10 I=1,N

C  ... COMPUTE KINEMATICS ...

DC1=CTAI(I)
RR=DSIN(DC1)-DSIN(CTAI4)*ARC4/ARC1
ES=DCOS(DC1)-DCOS(CTAI4)*ARC4/ARC1
DC14=DC1-CTA4

TE=(ARC4*2+ARC1**2-ARC2**2-ARC3**2)/(2.0D0+ARC1

* * ARC3)-DCOS(DC14)*ARC4/ARC3

PS=RR**2+ES**2-TE**2
TY=RR-DSQRT(PS)
TX=ES+TE

DC3=2.0D0*DATAN2(TY, TX)

YYY=ARC3*DSIN(DC3)+ARC4*DSIN(CTAI4)-ARC1*DSIN(DC1)
XXX=ARC3*DCOS(DC3)+ARC4*DCOS(CTAI4)-ARC1*DCOS(DC1)

DC2=DATAN2(YYY, XXX)

DC31=DC3-DC1
DC21=DC2-DC1
DC23=DC2-DC3

C2DU=ARC1*DSIN(DC31)*CTAI/((ARC2*DSIN(DC23))
C3DU=ARC1*DSIN(DC21)*CTAI/((ARC3*DSIN(DC23))

C

DC1L=DC1+ALMD1
DC2L=DC2+ALMD2
DC3L=DC3+ALMD3

X1DDU=-RR*DCOS(DC1L)*CTAI**2
Y1DDU=-RR*DSIN(DC1L)*CTAI**2

X2DDU=ARC1*DCOS(DC1)*CTAI**2+RR*(C2DDU+DSIN(DC2L)
+2C2DDU**2*DCOS(DC2L)

Y2DDU=ARC1*DSIN(DC1)*CTAI**2+RR*(C2DDU+DCOS(DC2L)

Y3DDU=RR3(C3DDU+DSIN(DC3L)+C3DDU**2*DCOS(DC3L)

Y3DDU=RR3(C3DDU+DCOS(DC3L)-C3DDU**2*DSIN(DC3L)

C

DC2L1 = DC2L - DC1

A2U = A12+C2DDU + AMAS2+RR2*ARC1*DSIN(DC2L1)*CTAI**2
A3U = A13*C3DDU
ZSUOM = (1.25D+00*CTAI)**2
SUBROUTINE MONIT(NIXC, FCIGCIISTATEpGPJRNMICONDIPOSDEFI
NITERjNFjIW? LIUpUjLUý

IMPLICIT REAL*B(A-HIP-Z)
DIMENSION SC(N), U(LU), XCCN)
INTEGER IU(LIU)pISTATE(N)
LOGICAL*POSDEF

WRITE(6,1110) MITERINFIFCIGPJRNM
WRITE(6j1120)

DO 100 J=1,N
ISJ=ISTATE(J)
IF(ISJ .GT. 0) GOTO 20
ISJ=-ISJ
GOTO (40,60,80) , ISJ
Listing of CONTACT at 16:17:27 on JUL 23, 1982 for CCid=MCB8

```
C 20 WRITE(6,1130) J, XC(J), GC(J)
GOTO 100
C 40 WRITE(6,1140) J, XC(J), GC(J)
GOTO 100
C 60 WRITE(6,1150) J, XC(J), GC(J)
GOTO 100
C 80 WRITE(6,1160) J, XC(J), GC(J)
GOTO 100
C 100 CONTINUE
C
IF(COND .EQ. 0.0D0) RETURN
IF(COND .LE. 1.0D+6) GOTO 120
C
WRITE(6,1170)
GOTO 140
C
120 WRITE(6,1180) COND
C
140 IF(. NOT. POSDEF) WRITE(6,1190)
C
RETURN
C
1110 FORMAT(/3HOITNS, 5X, 8HFN EVALS, 11X, 8HFN VALUE, 11X,
* 21HNNORM OF PROJ GRADIENT/I4,6X,I5,2(6X,1PE20.4))
1120 FORMAT(3HO J, 11X, 4HX(J), 16X,4HG(J), 13X, 6HSTATUS)
1130 FORMAT(1H, I2, 1X, 1P2E20.4, 5X, 4HFREE)
1140 FORMAT(1H, I2, 1X, 1P2E20.4, 5X, 11HUPPER BOUND)
1150 FORMAT(1H, I2, 1X, 1P2E20.4, 5X, 11HLOWER BOUND)
1160 FORMAT(1H, I2, 1X, 1P2E20.4, 5X, 8HCONSTANT)
1170 FORMAT(50H0ESTIMATED CONDITION NUMBER OF PROJECTED HESSIAN I,
* 18HS MORE THAN 1.0E+6)
1180 FORMAT(50H0ESTIMATED CONDITION NUMBER OF PROJECTED HESSIAN =, 1H , 1PE10.2)
1190 FORMAT(50HOPROJECTED HESSIAN MATRIX IS NOT POSITIVE DEFINITE)
C
END
C
SUBROUTINE RESULT(M, ITITLE)
IMPLICIT REAL*B(A-H,P-Z)
DIMENSION ITITLE(18)
COMMON /RESLT/AMASS1, RRS1, ALMDS1, AIS1, AMASS2, RRS2, ALMDS2, AIS2,
* AMASS3, RRS3, ALMDS3, AIS3, F12X(360), F12Y(360),
* F23X(360), F23Y(360), F43X(360), F43Y(360),
* F41X(360), F41Y(360), PID
C
WRITE(7) M, ITITLE
WRITE(7) (F12X(I), F12Y(I), F23X(I), F23Y(I), F43X(I), F43Y(I),
* F41X(I), F41Y(I), I=1, M)
```
Listing of CONTACT at 16:17:27 on JUL 23, 1982 for CCid=MCB8

407 DL = 1.0D+03
408 DLC = 1.0D+06
409 DG = 3.6D+02/PID
410 RRS1 = RRS1 * DL
411 RRS2 = RRS2 * DL
412 RRS3 = RRS3 * DL
413 ALMDS1 = ALMDS1 * DG
414 ALMDS2 = ALMDS2 * DG
415 ALMDS3 = ALMDS3 * DG
416 AIS1 = AIS1 * DLC
417 AIS2 = AIS2 * DLC
418 AIS3 = AIS3 * DLC
419 C
420 WRITE(6,1200)
421 WRITE(6,1210) AMASS1,RRS1,ALMDS1,AIS1,AMASS2,RRS2,ALMDS2,AIS2,
422 * AMASS3,RRS3,ALMDS3,AIS3
423 C
424 RETURN
425 C
426 1200 FORMAT('ADDED MASS PARAMETERS : -'/'38X,'POSITION OF C. OF M. ',
427 * /10X,'LINK',10X,'MASS',10X,'RADIUS',10X,'ANGLE',
428 * 9X,'INERTIA')
429 1210 FORMAT('CRANK',4X,4E15.6/8X,'COUPLER',2X,4E15.6
430 * /8X,'FOLLOWER',1X,4E15.6)
431 C
432 END
APPENDIX IID

LISTING OF COMPUTER PROGRAM

PINFORCE
C PROGRAM FOR PRODUCING JOINT FORCE PLOTS FOR FOUR-BAR LINKAGES

C

PI=4*ATAN(1.0)

READ(7) M, ITITLE
READ(7) (F12X(I), F12Y(I), F23X(I), F23Y(I), F43X(I), F43Y(I),
* F41X(I), F41Y(I), I=1,M)

DO 5 I=1,M
    P12X(I) = F12X(I)
    P12Y(I) = F12Y(I)
    P23X(I) = F23X(I)
    P23Y(I) = F23Y(I)
    P43X(I) = F43X(I)
    P43Y(I) = F43Y(I)
    P41X(I) = F41X(I)
    P41Y(I) = F41Y(I)

5 CONTINUE

CALL PSPACE(0.20, 0.45, 0.55, 0.80)
VMX = -1.0E+04
VMN = 1.0E+04
CALL SKALE(P41X, VMX, VMN, M)
CALL SKALE(P41Y, VMX, VMN, M)
ST = 0.1 * (VMX - VMN)
EXP=VMX+ST
EXN=VMN-ST
CALL ANOTAT(ST, ANO)
CALL HAP(EXN, EXP, EXP+6.0*ST, EXP-6.0*ST)
CALL DENSTY(2)
CALL CTRSETM
CALL CTRMAG(16)
CALL PLOTCS(EXN, EXP+6.0*ST, ITITLE, 72)
CALL CTRMAG(7)
CALL AXESSI(ANO, ANO)
CALL CTRSET(2)
CALL DENSTY(1)
CALL PTPLOT(P41X, P41Y, 1, M, 34)
CALL DENSTY(2)
CALL CURVE(P41X, P41Y, 1, M)
CALL DENSTY(1)
CALL CTRMAG(9)
Listing of PINFORCE at 16:34:02 on JUL 23, 1982 for CCid=MCCB

59 CALL PLOTNI(P41X(H1),P41Y(H1),N1,1)
60 CALL SUPFIX
61 CALL TYPECS('0',1)
62 CALL NORMAL
63 CALL PLOTNI(P41X(H2),P41Y(H2),N2,3)
64 CALL SUPFIX
65 CALL TYPECS('0',1)
66 CALL NORMAL
67 CALL PLOTNI(P41X(H3),P41Y(H3),N3,3)
68 CALL SUPFIX
69 CALL TYPECS('0',1)
70 CALL NORMAL
71 CALL DENSITY(2)
72 CALL PLOTCS(EXN,EXP+ST, 'FORCE EXERTED BY FRAME ON CRANK',31)
73 CALL DENSITY(1)
74 CALL BORDER
75 CALL PSPACE(0.60,0.85,0.55,0.80)
76 VMX = -1.0E+04
77 VMN = 1.0E+04
78 CALL SCALED(PI2X,VMX,VMN,M)
79 CALL SCALED(PI2Y,VMX,VMN,M)
80 ST = 0.1*(VMX-VMN)
81 EXP=VMX+ST
82 EXP=VMN-ST
83 CALL ANOTAT(ST,ANO)
84 CALL MAP(EXN,EXP+ST,EXP)
85 CALL DENSITY(2)
86 CALL CTRSET(1)
87 CALL CTRMAG(7)
88 CALL AXESSI(ANO,ANO)
89 CALL CTRSET(2)
90 CALL DENSITY(1)
91 CALL PTPLOT(PI2X,PI2Y,1,M,34)
92 CALL DENSITY(2)
93 CALL CURVEC(PI2X,PI2Y,1,M)
94 CALL DENSITY(1)
95 CALL CTRMAG(9)
96 CALL PLOTNI(PI2X(H1),PI2Y(H1),N1,1)
97 CALL SUPFIX
98 CALL TYPECS('0',1)
99 CALL NORMAL
100 CALL PLOTNI(PI2X(H2),PI2Y(H2),N2,3)
101 CALL SUPFIX
102 CALL TYPECS('0',1)
103 CALL NORMAL
104 CALL PLOTNI(PI2X(H3),PI2Y(H3),N3,3)
105 CALL SUPFIX
106 CALL TYPECS('0',1)
107 CALL NORMAL
108 CALL DENSITY(2)
109 CALL PLOTCS(EXN,EXP+ST, 'FORCE EXERTED BY CRANK ON COUPLER',33)
110 CALL DENSITY(1)
111 CALL BORDER
112 CALL PSPACE(0.20,0.45,0.15,0.40)
117 VMX = -1.0E+04
118 VMN = 1.0E+04
119 CALL SKALE(P23X, VMX, VMN, M)
120 CALL SKALE(P23Y, VMX, VMN, M)
121 C
122 ST = 0.1 * (VMX - VMN)
123 EXP=VMX+ST
124 EXN=VMN-ST
125 CALL ANOTAT(ST, ANO)
126 C
127 CALL MAP(EXN, EXP, EXN, EXP)
128 CALL DENS(TY(2)
129 CALL CTRSET(1)
130 CALL CTRMAG(7)
131 CALL AXESSI(ANO, ANO)
132 CALL CTRSET(2)
133 CALL DENS(TY(1)
134 CALL PTPL0T(P23X, P23Y, 1, M, 34)
135 CALL DENS(TY(2)
136 CALL CURVEC(P23X, P23Y, 1, M)
137 CALL DENS(TY(1)
138 CALL CTRMAG(9)
139 CALL PLOT NI(P23X(M1), P23Y(M1), M1, 1)
140 CALL SUPF I X
141 CALL TYPECS('O', 1)
142 CALL NORMAL
143 CALL PLOT NI(P23X(M2), P23Y(M2), M2, 3)
144 CALL SUPF I X
145 CALL TYPECS('O', 1)
146 CALL NORMAL
147 CALL PLOT NI(P23X(M3), P23Y(M3), M3, 3)
148 CALL SUPF I X
149 CALL TYPECS('O', 1)
150 CALL NORMAL
151 CALL DENS(TY(2)
152 CALL PLOT CS(EXN, EXP+ST, 'FORCE EXERTED BY COUPLER ON FOLLOWER', 36)
153 CALL DENS(TY(1)
154 CALL BORDER
155 C
156 CALL PSPACE(0.60, 0.85, 0.15, 0.40)
157 VMX = -1.0E+04
158 VMN = 1.0E+04
159 CALL SKALE(P43X, VMX, VMN, M)
160 CALL SKALE(P43Y, VMX, VMN, M)
161 C
162 ST = 0.1 * (VMX - VMN)
163 EXP=VMX+ST
164 EXN=VMN-ST
165 CALL ANOTAT(ST, ANO)
166 C
167 CALL MAP(EXN, EXP, EXN, EXP)
168 CALL DENS(TY(2)
169 CALL CTRSET(1)
170 CALL CTRMAG(7)
171 CALL AXESSI(ANO, ANO)
172 CALL CTRSET(2)
173 CALL DENS(TY(1)
174 CALL PTPL0T(P43X, P43Y, 1, M, 34)
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175 CALL DENSITY(2)
176 CALL CURVEC(P43X,P43Y,1,M)
177 CALL DENSITY(1)
178 CALL CTRMAG(9)
179 CALL PLOTFN(P43X(M1),P43Y(M1),M1,1)
180 CALL SUFFIX
181 CALL TYPECS('O',1)
182 CALL NORMAL
183 CALL PLOTFN(P43X(M2),P43Y(M2),M2,3)
184 CALL SUFFIX
185 CALL TYPECS('O',1)
186 CALL NORMAL
187 CALL PLOTFN(P43X(M3),P43Y(M3),M3,3)
188 CALL SUFFIX
189 CALL TYPECS('O',1)
190 CALL NORMAL
191 CALL DENSITY(2)
192 CALL PLOTCS(EXN,EXP+ST,'FORCE EXERTED BY FRAME ON FOLLOWER',34)
193 CALL DENSITY(1)
194 CALL BORDER
195 C
196 CALL CTRMAG(20)
197 CALL GREN
198 STOP
199 END
200 C
201 C * * * * * * * * * * * * * * * * * * * * *
202 C
203 C SUBROUTINE SKALE(VAR,VMX,VMN,N)
204 C
205 REAL VAR(N)
206 C
207 DO 10 I=1,N
208 IF (VMX .LT. VAR(I)) VMX=VAR(I)
209 10 IF (VMN .GT. VAR(I)) VMN=VAR(I)
210 C
211 RETURN
212 END
213 C
214 C * * * * * * * * * * * * * * * *
215 C
216 C SUBROUTINE ANOTAT(ST,AND)
217 C
218 DT = 4.0 * ST
219 C
220 IF (DT .GE. 200.0) AND = FLOAT (IFIX (DT / 200.0)) * 200.0
221 IF (DT .GE. 200.0) GO TO 20
222 IF (DT .GE. 50.0 .AND. DT .LT. 200.0)
223 * AND = FLOAT (IFIX (DT / 25.0)) * 25.0
224 IF (DT .GE. 50.0) GO TO 20
225 IF (DT .GE. 10.0 .AND. DT .LT. 50.0)
226 * AND = FLOAT (IFIX (DT / 5.0)) * 5.0
227 IF (DT .GE. 10.0) GO TO 20
228 IF (DT .GE. 2.0 .AND. DT .LT. 10.0)
229 * AND = FLOAT (IFIX (DT / 2.0)) * 2.0
230 IF (DT .GE. 2.0) GO TO 20
231 IF (DT .GE. 0.5 .AND. DT .LT. 2.0)
232 * AND = FLOAT (IFIX (DT / 0.25)) * 0.25
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233 IF (DT .GE. 0.5) GO TO 20
234 IF (DT .GE. 0.1 .AND. DT .LT. 0.5)
235 * AND = FLOAT (IFIX (DT / 0.05)) * 0.05
236 IF (DT .GE. 0.1) GO TO 20
237 IF (DT .GE. 0.02 .AND. DT .LT. 0.1)
238 * AND = FLOAT (IFIX (DT / 0.02)) * 0.02
239 IF (DT .GE. 0.02) GO TO 20
240 IF (DT .GE. 0.005 .AND. DT .LT. 0.02)
241 * AND = FLOAT (IFIX (DT / 0.005)) * 0.005
242 IF (DT .GE. 0.005) GO TO 20
243 IF (DT .LT. 0.005) AND = FLOAT (IFIX (DT / 0.001)) * 0.001
244 C
245 20 RETURN
246 END